Effect of subgrade compressibility on the reinforcing performance of railroad geogrids: insights from finite element analysis

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ABSTRACT
Ballasted railway embankments typically consist of a superstructure and a substructure. The superstructure is composed of the rails, fasteners, and ties and is supported by the substructure, which is a multi-layer system comprising of a ballast layer, a subballast layer, and a subgrade. Under repeated train loading, railroad ballast progressively settles and spreads laterally, leading to the development of differential settlement along the tracks. The behavior of a ballasted substructure can be improved by incorporating one or several geogrids in some of its strata to minimize settlement, prevent ballast lateral spreading, reduce ballast degradation, increase the substructure's bearing capacity, and reduce the magnitude of stresses transferred to the subgrade. The reinforcing action of a railroad geogrid is tied to the subgrade compressibility, its aperture size, and its depth of placement within the substructure. As such, this paper explores the influence of subgrade compressibility on the reinforcing performance of railroad geogrids by presenting the results of a parametric study conducted using finite element analysis.

RÉSUMÉ
Les voies ferrées ballastées font l'objet de l'accumulation progressive de tassements différentiels causée en partie par le tassement progressif du ballast sous l'effet cyclique des efforts engendrés par le passage de trains. L'utilisation de géogrilles permet de renforcer les couches d'assise des chemins de fer afin de réduire leur tassement au fil du temps. L'efficacité de ces dernières dépend par ailleurs de la taille de leurs ouvertures, de l'endroit où elles sont placées ainsi que de la qualité de la plateforme. Cet article propose d'étudier l'impact de la qualité de la plateforme sur l'efficacité de géogrilles placées dans les couches d'assise de voie ferrées en présentant les résultats d'une étude paramétrique réalisée en modélisant des chemins de fer avec la méthode des éléments finis.

1 INTRODUCTION

A typical ballasted railway embankment (see Figure 1) is composed of a superstructure comprising the rails, fasteners, and the ties overlying a substructure, which is a multi-soil layer system that consists of three strata (Li et al. 2015; Selig and Waters 1994). The upper stratum is the ballast layer and it is generally made of coarse, angular, uniformly graded crushed stone. Its primary functions include supporting the ties, resisting the train loads and transferring them to the underlying stratum, providing drainage, providing ample void space to accommodate particle rearrangement, and storing fouling material. The ballast is underlain by a well-graded granular layer called the subballast that performs functions akin to the ballast's while also separating the latter from the subgrade, thereby ensuring that the two materials do not intermix. The bottommost layer of the substructure is the subgrade. It provides a bearing platform on which the entire track structure rests. The subgrade plays a central role in the stability of the track structure and is often the root cause of track failure or excessive maintenance needs (Li and Selig 1995).

The occurrence of permanent settlement along railway tracks poses a threat to the track riding safety and warrants the need for either costly maintenance operations or the imposition of speed restrictions along track sections affected by excessive track subsidence (Hussaini and Sweta 2020; Li et al. 2015). Settlement mainly arises from the ballast and/or subgrade layers. In the ballast layer, non-recoverable vertical deformations accumulate over time owing to the fact that initially, the ballast aggregate is in a relatively loose state and gets progressively pushed into a denser packing under repeated train loading. This leads to a reduction in the ballast layer's void ratio as well as lateral spreading and degradation of the aggregate which all contribute to the build-up of settlement (Bathurst and Raymond 1987; Sussmann, Ruel, and Chrismer 2012). Excessive track subsidence may also occur as a result of issues related to the subgrade soil that can generally be attributed to three factors: loading, soil type, and environmental conditions (Li and Selig 1995). Repeated dynamic train wheel loads are of particular concern when the subgrade consists of fine-grained soils such as silt or clay due to their low strength and high plasticity that make them vulnerable to accumulating large deformations under cyclic loading (Li and Selig 1995).

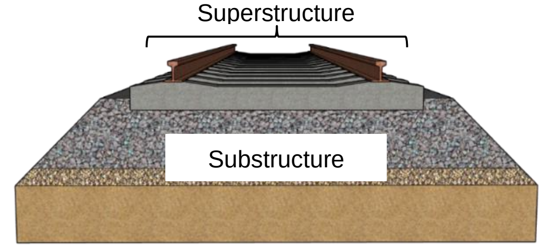

Figure 1. Typical Ballasted Railway Tracks

It is against this background that geosynthetics such as geogrids have been introduced in ballasted railway track substructures in a bid to minimize the build-up of permanent track settlement. Geogrids are sheets of polymeric materials composed of large openings, i.e., apertures, bordered by longitudinal and transverse ribs that are used to reinforce earth structures such as roads, railroads, embankments, slopes, etc. (Desbrousses and Meguid 2021; Shokr, Meguid, and Bhat 2021, 2022). Their reinforcing action hinges on their ability to develop a strong mechanical bond with the surrounding soil by allowing its particles to strike through their plane and become tightly wedged in their apertures (Giroud and Han 2004).

In railroad applications, the *Manual for Railway Engineering* (AREMA 2010) states that geogrids are mainly used to perform one of two functions depending on the subgrade strength: (1) when the subgrade is relatively firm, geogrids may be placed within or at the bottom of the ballast layer to reinforce it, reduce its settlement, and increase the length of its maintenance cycle, (2) when the subgrade is weak, geogrids can be placed directly above the subgrade to increase its bearing capacity.

Similarly, research has demonstrated that the performance of a geogrid placed in a ballasted railway substructure is governed by the size of its apertures in comparison to the surrounding soil, its placement location, and the subgrade strength (Bathurst and Raymond 1987; Brown, Kwan, and Thom 2007; Gao and Meguid 2018; Hussein and Meguid 2013; Jewell 1988; Jewell et al. 1984).

The size of a geogrid's apertures affects its ability to develop a bond with the surrounding soil. Numerical and experimental studies conducted on geogrid-reinforced railroad ballast suggest that there exists an optimal range of aperture size to nominal ballast diameter ratio to achieve a maximum geogrid interlock of 1.2 to 1.6 (Brown, Kwan, and Thom 2007; McDowell et al. 2006; McDowell and Stickley 2006) or 0.95 to 1.2 (Indraratna, Hussaini, and Vinod 2013; Indraratna, Karimullah Hussaini, and Vinod 2012; Indraratna and Nimbalkar 2013).

The depth (D_r) at which a geogrid is placed below the bottom of the ties influences its ability to reinforce a ballasted substructure (Das 2016; Shin and Das 2000). Bathurst and Raymond (1987) performed ballast box tests on geogrid-reinforced ballast and recommended that geogrids be placed at a depth below the tie corresponding to a ratio D_r/B of 0.2-0.4 where B is the tie width. Raymond and Ismail (2003) drew similar conclusions after conducting 1/10th scale tests and finite element analyses of a tie resting on geogrid-reinforced ballast and recommended D_r/B ratios in the range of 0.2-0.5. The optimum placement depth of a geogrid is also influenced by the fact that the ballast layer is periodically subjected to invasive maintenance operations such as tamping that disturb the upper 100-150mm of the layer and could damage any geosynthetic reinforcement located in that zone (Brown, Kwan, and Thom 2007; Li et al. 2015). As such, it is recommended that geogrids be placed at least 200mm below the bottom of the ties (Bathurst and Raymond 1987; Hussaini, Indraratna, and Vinod 2016).

The strength of the subgrade is a defining factor that dictates the significance of using geogrids. Large-scale ballast box tests conducted by Bathurst and Raymond (1987) and Brown et al. (2007), as well as triaxial tests performed by Yu et al. (2019) on geogrid-reinforced ballast/subballast resting on subgrades on varying compressibility, revealed that significant settlement reductions were achieved when a geogrid was used when the subgrade was weak but that only minor settlement reductions were observed when the subgrade was firm.

Numerical methods have been used to provide insight into the behavior of geogrid-reinforced railroad substructures using either finite element modeling (FEM) or discrete element modeling (DEM). DEM finds most of its applications in simulating the behavior of railroad ballast with and without geogrid inclusions owing to its ability to consider each particle in a granular assembly individually and describe the interaction between ballast particles and geogrids at the microscopic level (Ferellec and McDowell 2012; Gao and Meguid 2018; Tran, Meguid, and Chouinard 2013; Wang, Meguid, and Mitri 2021). On the other hand, in FEM, the constituent materials of a railway track structures are treated as continua and discretized into finite elements each with its own degrees of freedom, shape, and nodes at which the constitutive equations used to describe their behavior are solved to compute stresses and strains (Alabbasi and Hussein 2021). Railroad track structures may be modeled either as 2D structures (Desai and Siriwardane 1982; Indraratna and Nimbalkar 2011; Jiang and Nimbalkar 2019; Shahin and Indraratna 2006; Xu and Zsáki 2021) by assuming plane-strain conditions or as 3D structures (Chawla and Shahu 2016; Sowmiya, Shahu, and Gupta 2014).

In this study, a two-dimensional finite element model of a ballasted railway track structure is developed using PLAXIS 2D v22 (Bentley Systems 2022) to investigate the effect of subgrade strength on the settlement reduction derived from the inclusion of a geogrid placed at different locations within the substructure following the recommendations of the *Manual for Railway Engineering* (AREMA 2010).

2 FINITE ELEMENT ANALYSIS

2.1 Model Validation

Field measurements recorded on the FAST research tracks by Stewart and Selig (1982) and results of finite element analyses simulating the FAST tracks are used to validate the model developed in this study. The FAST tracks have a gauge length of 1.7m, support 145kN train wheel loads, and consist of a 380mm-thick ballast layer overlying a 150mm-thick subballast layer underlain by the subgrade. Additional details about the FAST tracks may be found in works published by Stewart and Selig (1982) and Adegoke (1979). The constitutive models used to represent the various track materials are listed in Table 1 and the results generated by the model are summarized in Table 2. The subballast strain (ε) and subgrade deviator stress (σ_d) predicted by the model are in good agreement with the range of quantities measured on the FAST tracks and the results from other finite element analysis models. Similar to the other FE models, the present model underestimates the ballast strain although this discrepancy with the experimental data may be attributed to the fact that Stewart and Selig (1982) reported recording high ballast strains due to tie lift-up and tie-ballast gap closure.

Table 1. Constitutive Models Used for Validation

Material	Model	γ (kN/m^3)	*E* (kPa)	*v*	*c'* (kPa)	*Φ'* (°)
Steel Rail	LE [a]	78.5	211x10^6	0.33	N/A	N/A
Timber Tie	LE	10	10.35x10^6	0.37	N/A	N/A
Ballast	MC [b]	15.6	207x10^3	0.2	0	45
Subballast	MC	16.7	138x10^3	0.3	0	30
Subgrade	MC	17	34x10^3	0.3	22	30

[a] LE: Linear Elastic; [b] MC: Mohr-Coulomb

Table 2. Comparison Between the Model and Data Reported in other Studies

	Ballast *ε*	Subballast *ε*	Subgrade σ_d (kPa)
FAST Track	0.00392-0.00582	0.000396-0.000783	30.3-60.6
GEOTRACK Model[1]	0.0005	0.0005	71.2
Shahin & Indraratna (2006)	0.0003	0.00057	66.6
Present Study	0.0006	0.00068	69.7

[1]GEOTRACK Model used by Stewart and Selig (1982)

2.2 General Track Geometry

The ballasted railway track structure considered in this study is shown in Figure 2. The tracks support freight trains with an average loaded car static wheel load of 33.4kips (148.63kN) and a wheel diameter of 36in (915mm) (Van Dyk et al. 2017). The dynamic wheel load applied by moving trains on the rails differs from the static wheel load. To design the tracks, the *Manual for Railway Engineering* (AREMA 2010) recommends multiplying the static wheel load by an impact factor to calculate the design dynamic wheel load using Eq.1:

$$P_d=P_s\times IF \quad [1]$$

Where P_d is the dynamic wheel load, P_s is the static wheel load, and *IF* is the impact factor given by Eq. 2.

$$IF=1+\frac{33V}{100D} \quad [2]$$

Where *V* is the train's velocity (in miles per hour) and *D* is the train wheel diameter (in inches).

In this paper, the train velocity is taken as 25mph (40.2km/h) to represent the typical average speed of freight trains in Canada (Statistics Canada 2019), giving an influence factor *IF* and a dynamic wheel load P_d of:

$$IF=1+\frac{33V}{100D}=1+\frac{33\times 25}{100\times 36}=1.23 \quad [3]$$

$$P_d=P_s\times IF=33.4\times 1.23=41.05\text{kips}=183\text{kN} \quad [4]$$

The railway is standard gage, meaning that the inside edges of the rails are 4ft 8 1/2in (1,435mm) apart. The rails are 115lbs rails and are supported by 8ft long (2,440mm), 6in thick (150mm), and 8in wide (150mm) wooden ties. The superstructure is underlain by a substructure composed of a 12in thick (300mm) ballast layer underlain by a 6in thick (150mm) subballast resting on a 5m deep subgrade.

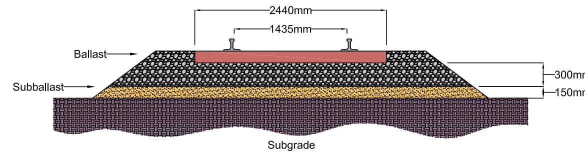

Figure 2. Modeled Railway Tracks

2.3 Parametric Study

The goal of this study is to evaluate the effect of subgrade strength on the ability of geogrid reinforcement to minimize the settlement of a tie supporting a 183kN freight train wheel load resting on a ballasted substructure. As such, three different subgrade soils with moduli of elasticity of 80MPa, 25MPa, and 12.5MPa representing railroad subgrades of good, medium, and low strength respectively (Profillidis 2017) are considered.

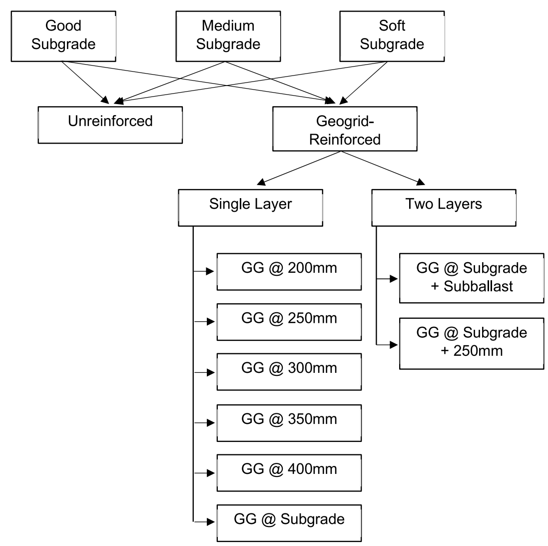

Figure 3. Cases Considered in the Parametric Study

For each subgrade type, the settlement of the tie supporting train loading is evaluated for an unreinforced substructure and reinforced substructures by monitoring the settlement of the rail seat. The substructure is reinforced through the inclusion of geogrid reinforcement initially placed 200mm below the base of the tie. The placement depth of the grid is then increased in subsequent simulations in 50mm increments until the grid is located directly above the subgrade, thereby covering the full range of recommended geogrid placement locations outlined in the *Manual for Railway Engineering*. The effect of reinforcing the substructure with two geogrid layers is then investigated by placing the first layer above the subgrade and placing the second geogrid either at the bottom of the ballast layer or 250mm below the base of the tie. The cases considered in the parametric study are summarized in Figure 3.

2.4 Finite Element Model and Constitutive Models

The railway embankment shown in Figure 2 is modeled as a two-dimensional structure by assuming plane-strain conditions using PLAXIS 2D as shown in Figure 4. Owing to the track structure's symmetry, only half of it is modeled. After conducting a sensitivity analysis, it was decided to discretize the model using 3,369 15-noded triangular plane-strain elements. The mesh is constructed such that fine elements are used to discretize a 3.5m by 5m area of the subgrade below the subballast to allow for a more accurate simulation of its behavior.

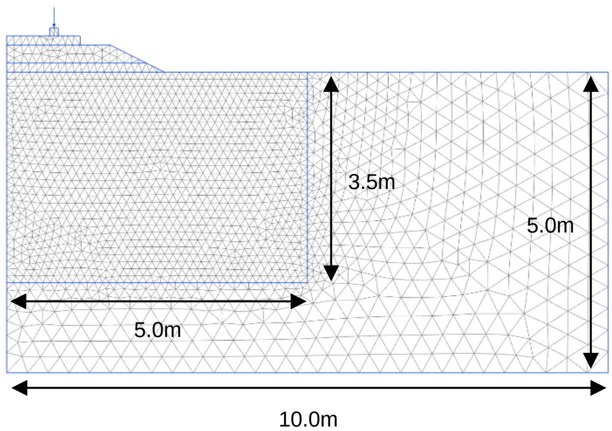

Figure 4. 2D Plante-Strain Model of the Railway Embankment

The 115lbs rail is represented by a 130mm by 140mm rectangle with a moment of inertia about its neutral axis that matches that of the actual 115lbs rail. As recommended by Shahin and Indraratna (2006), the fastening system connecting the rails to the ties is simulated restraining the movement in the *x*-direction of the corner nodes of the rails in contact with the tie.

The analyses presented in this paper are based on the constitutive models listed in Table 3. Every soil is modeled using the Mohr-Coulomb model with parameters based on data published by Desai and Siriwardane (1982), Profillidis (2017), Indraratna and Nimbalkar (2011), and Jiang and Nimbalkar (2019).

Geogrids are modeled using 5-noded line elements that possess two translational degrees of freedom at each note with interface elements being added at their top and bottom surfaces such that the full interaction between the geogrids and the surrounding soil(s) may be simulated (Bentley Systems 2021). The geogrid considered in this study is a large-aperture geogrid designed specifically for railroad applications. The properties of this grid were examined by Desbrousses et al. (2021) who performed single-rib tensile tests on samples of the material following Method A of ASTM D6637. The tensile load-strain (N-ε) curve (Figure 5) published by Desbrousses et al. (2021) is input in PLAXIS 2D to model the geogrid's behavior using the elastoplastic (N-ε) model to capture the nonlinear nature of the grid's behavior.

Table 3. Constitutive Models and Parameters

Material	Model	γ (kN/m^3)	*E* (kPa)	*v*	*c'* (kPa)	*Φ'* (º)
Steel Rail	LE [a]	78.5	210x10^6	0.3	N/A	N/A
Timber Tie	LE	10	25x10^6	0.25	N/A	N/A
Ballast	MC [b]	15.6	130x10^3	0.2	0	45
Subballast	MC	16.7	100x10^3	0.3	0	30
Good Subgrade	MC	18	80x10^3	0.3	0	35
Medium Subgrade	MC	17	25x10^3	0.3	10	20
Soft Subgrade	MC	16	12.5x10^3	0.4	15	10

[a] *LE: Linear Elastic;* [b] *MC: Mohr-Coulomb*

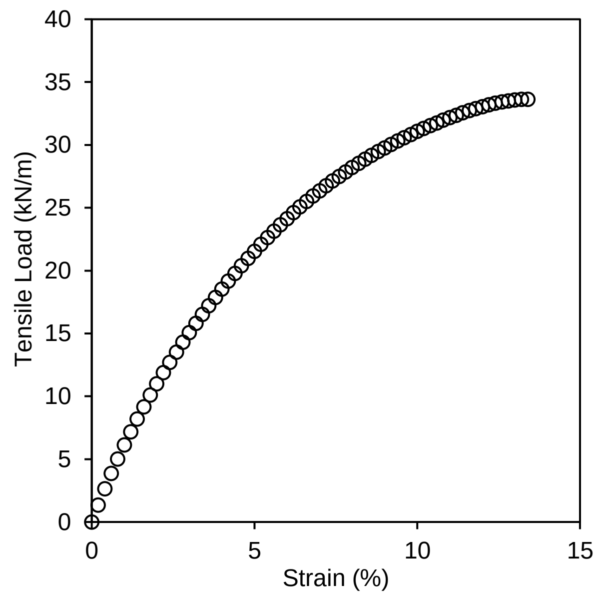

Figure 5. Tensile Load-Strain Curve of the Geogrid adapted from Desbrousses et al. (2021)

3 RESULTS

3.1 Unreinforced Ballasted Railway Tracks

Figure 6 shows the shaded settlement plots for the unreinforced ballasted railway embankments resting on the good, medium, and soft subgrades subjected to a 183kN freight train wheel load. The smallest settlement occurred in the track structure underlain by the good subgrade, with a maximum settlement below the rail seat of 9.07mm. The smaller strengths that characterize both the medium and soft subgrades translate into the development of greater settlements that affect zones extending deeper into the subgrade. The maximum rail seat settlement recorded for the medium and soft subgrades is 34.41mm and 69.19mm respectively.

(a) (b) (c)

Figure 6. Shaded Settlement Plots for Unreinforced Tracks Resting on a (a) Good, (b) Medium, and (c) Soft Subgrade

3.2 Reinforced Ballasted Railway Tracks

The effect of embedding a geogrid in a ballasted substructure on the settlement of the rail seat is investigated by placing a single geogrid layer at various depths below the bottom of the tie. The geogrid is first placed 200mm below the base of the tie and its placement depth is then increased in 50mm increments until the grid lies directly above the subgrade. Table 4 compares the rail seat settlement for unreinforced and reinforced embankments resting on the three different subgrades of varying strengths.

The inclusion of a geogrid in the ballasted substructure overlying the good subgrade yields minimal improvements, with a maximum settlement reduction of 3.47% achieved by the geogrid placed 200mm below the base of the tie. The small settlement reduction brought about by the presence of the grid quickly subsides as its placement depth is increased, with the grids placed at depths of 300mm or more decreasing the rail seat settlement by less than 2%. The trend observed for the good subgrade suggests that minor benefits may be derived from the presence of geogrid reinforcement in railway embankments resting on competent subgrades.

The reinforcing action of the geogrid becomes more apparent for the tracks supported by the medium subgrade. Similar to the good subgrade, the maximum settlement reduction is achieved by laying the geogrid 200mm below the base of the tie, resulting in a rail seat settlement 9.49% smaller than the unreinforced case. While a similar settlement reduction is obtained by placing a geogrid 250mm below the tie, placing the geogrid at the ballast/subballast interface or below has a detrimental impact on the reinforcement's ability to decrease the rail seat settlement. The worst performance of the grid occurs when it is placed at the subballast/subgrade interface with a rail seat settlement only 5.84% smaller than the one for the unreinforced tracks.

The greatest overall benefit of using a geogrid to reinforce the ballasted track substructure is obtained when the substructure is underlain by the soft subgrade. Placing the geogrid within the ballast layer, i.e., at depths ranging from 200 to 300mm, is the most effective at minimizing the rail seat subsidence, resulting in rail seat settlements more than 12% smaller than for the unreinforced case. The efficiency of the geogrid then progressively wanes as its placement depth increases, reaching a minimum settlement reduction of 7.59% when it is placed above the subgrade.

The results suggest that a single layer of geogrid reinforcement is most effective at decreasing the rail seat settlement when it is placed within the ballast layer in a track substructure supported by a relatively weak subgrade. In cases where railway tracks are underlain by weak subgrades, the *Manual for Railway Engineering* recommends placing a geogrid immediately above the subgrade to increase its bearing capacity. As such, the effect of using a geogrid placed above the subgrade in conjunction with a second geogrid layer placed either at the ballast/subballast interface or 250mm below the base of the ties is investigated. The rail seat settlement and the settlement reduction generated by the presence of two geogrids are compared to the results recorded for the unreinforced embankments and embankments reinforced with a single geogrid in Figures 7a and b respectively. The cases where the grids are placed above the subgrade and

Table 4. Rail Seat Settlement under Unreinforced and Reinforced Conditions

	Good Subgrade		Medium Subgrade		Soft Subgrade	
Case	Settlement (mm)	% Reduction	Settlement (mm)	% Reduction	Settlement (mm)	% Reduction
Unreinforced	9.07	--	34.41	--	69.19	--
GG* @ 200mm	8.75	3.47	31.14	9.49	60.50	12.56
GG @ 250mm	8.81	2.84	31.29	9.07	60.39	12.72
GG @ 300mm	8.95	1.35	31.47	8.54	60.69	12.29
GG @ 350mm	8.94	1.43	31.64	8.05	62.64	9.46
GG @ 400mm	8.97	1.09	31.97	7.09	62.88	9.13
GG @ Subgrade	8.91	1.78	32.40	5.84	63.94	7.59

**GG: Geogrid*

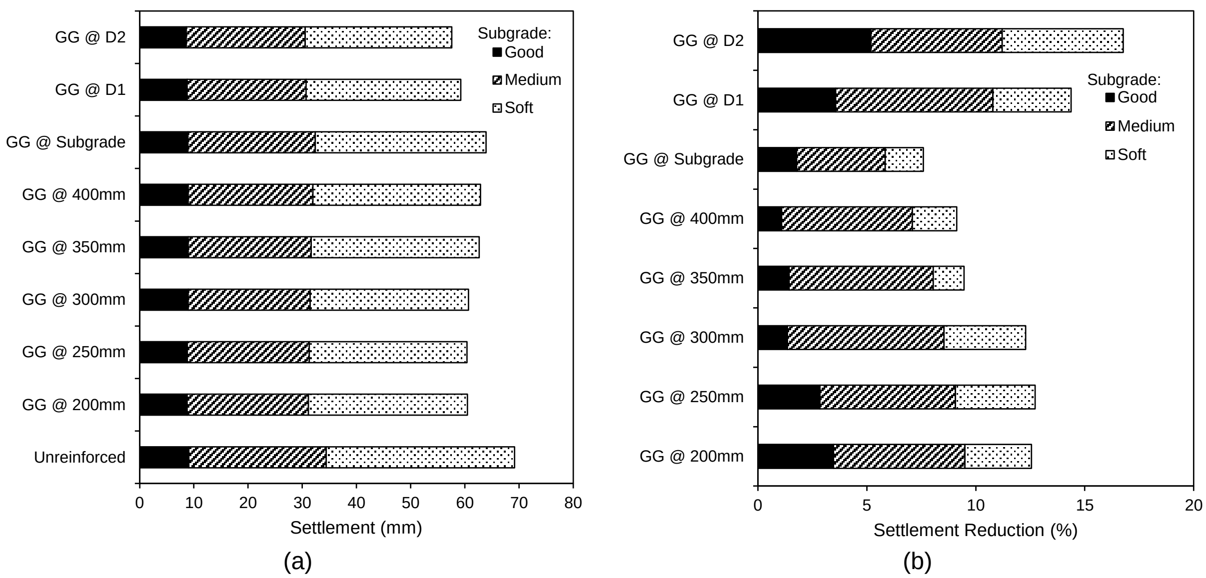

Figure 7. (a) Rail Seat Settlement for Unreinforced and Reinforced Embankments, (b) Settlement Reduction Achieved through the Inclusion of Geogrids

the subballast and above the subgrade and 250mm below the tie are labeled as GG @ D1 and GG @ D2 respectively in the aforementioned figures. For all three subgrade types, the embankments reinforced with two geogrids settle substantially less than those reinforced with a single geogrid, regardless of its placement location. Using a geogrid placed within the ballast in conjunction with one overlying the subgrade doubles the settlement reduction generated by a single geogrid placed above the subgrade. It is noteworthy that placing the second geogrid 250mm below the tie results in a smaller rail seat settlement than when it is placed above the subballast.

The results suggest that a single layer of geogrid reinforcement is most effective at decreasing the rail seat settlement when it is placed within the ballast layer in a track substructure supported by a relatively weak subgrade. In cases where railway tracks are underlain by weak subgrades, the *Manual for Railway Engineering* recommends placing a geogrid immediately above the subgrade to increase its bearing capacity. As such, the effect of using a geogrid placed above the subgrade in conjunction with a second geogrid layer placed either at the ballast/subballast interface or 250mm below the base of the ties is investigated. The rail seat settlement and the settlement reduction generated by the presence of two geogrids are compared to the results recorded for the unreinforced embankments and embankments reinforced with a single geogrid in Figures 7a and b respectively. The cases where the grids are placed above the subgrade and the subballast and above the subgrade and 250mm below the tie are labeled as GG @ D1 and GG @ D2 respectively in the aforementioned figures. For all three subgrade types, the embankments reinforced with two geogrids settle substantially less than those reinforced with a single geogrid, regardless of its placement location. Using a geogrid placed within the ballast in conjunction with one overlying the subgrade doubles the settlement reduction generated by a single geogrid placed above the subgrade. It is noteworthy that placing the second geogrid 250mm below the tie results in a smaller rail seat settlement than when it is placed above the subballast.

3.3 Limitations

It is important to appreciate that the results presented herein are affected by assumptions made during the modeling process. The ballasted railway tracks are idealized as a two-dimensional structure using a plane-strain assumption whereby the strain in the longitudinal direction along the tracks is assumed to be zero. Additionally, the plane-strain assumption implies that the ties are assumed to be continuous in the longitudinal direction, thereby neglecting the effect of tie spacing on the stresses induced in the substructure by passing trains. Train loading is applied on the tracks as an amplified static line load which overlooks the dynamic and cyclic nature of the train wheel loads and the fact that real wheel loads are point loads. The substructure materials are also treated as continua which is not an accurate representation of the highly discontinuous nature of the granular materials used in the ballast and subballast layers.

4 CONCLUSIONS

The parametric study presented in this paper investigates the effect of subgrade strength on the settlement reduction resulting from the presence of geogrids in the substructure of ballasted railway tracks. The results suggest that it is particularly beneficial to reinforce ballasted railway tracks with a geogrid when they are supported by weak subgrades in which train loading would be likely to trigger large settlements. However, geogrids only have a limited ability to minimize settlement when the tracks are supported by a competent subgrade. When a single geogrid layer is used to reinforce a ballasted substructure, maximum settlement reduction is obtained by placing it within the ballast layer. The efficiency of a single geogrid seems to wane as its placement depth below the tie increases. Combining the use of a geogrid placed immediately above the subgrade with a geogrid embedded in the ballast layer consistently results in smaller settlements than when only a single geogrid is used to reinforce the substructure. The effect of adding a geogrid layer in the ballast when a geogrid is laid above the subgrade doubles the settlement reduction that occurs when a single geogrid overlies the subgrade.

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