Canadian Geotechnical Journal
Revue canadienne de géotechnique

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2016-0562.R1
Manuscript Type:	Note
Date Submitted by the Author:	25-Jan-2017
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Keyword:	Reinforcement, geosynthetics, unpaved, location, finite element

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OPTIMUM LOCATION OF THE GEOGRID REINFORCEMENT IN UNPAVED ROAD

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ABSTRACT

This study evaluated the optimum location of a reinforcement layer to maximize the efficiency of the reinforcement inclusion in an unpaved road section. The analyses are used to investigate the optimum location of the reinforcement layer within the aggregate base course, (ABC) layer, and explain possible reason for the improvement in performance. A series of 3D FEM analyses were performed, and the strain and stress response of a reinforced unpaved road section with two different ABC thicknesses was evaluated. The analyses were conducted under cyclic loading with three different radii of the circular loaded area. The embedded depth of reinforcement was varied within the ABC layer. Results indicated that regardless of ABC layer thickness, the surface deformation is minimized when the reinforcement is embedded at a depth equal to half of the radius of the loaded area, ($D = 0.5r$). A higher tension force is mobilized in the reinforcement element when it is placed at $D = 0.5r$. It is also shown that the required thickness of ABC is reduced when the reinforcement layer is implemented at the depth at which the maximum vertical strain occurs. Depending on the thickness of the ABC layer, the FEA results indicated that reinforcement layer could be ineffectual if it is placed at the interface between the ABC and the subgrade layer as is traditionally the case.

Keywords: Reinforcement, geosynthetics, unpaved, location, finite element.

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INTRODUCTION

Over the years, many studies have been performed to investigate the deformation behavior of the reinforced unpaved road. These included small-scale and large-scale laboratory testing and full-scale field tests as well as numerical and analytical analyses, (e.g. Fannin and Sigurdsson 1996; Hufenus et al. 2005; Leng and Gabr 2006; Tingle and Jersy 2009; Chen et al. 2009; Cote et al. 2010; White et al. 2011; Abu-Farsakh et al. 2011; Cowell et al. 2012; Thakur et al. 2012; Qian et al. 2012; Saghebfar 2014; Tang et al. 2015; Sun et al. 2015; Palmeira and Gongora 2015). Several of these studies have been performed to evaluate the influence of factors such as the thickness of the aggregate base course (ABC), shear strength and stiffness properties of subgrade, location of the reinforcement layer within the ABC layer, and mechanical and geometric properties of geogrid, on deformation response of a reinforced unpaved road. Geosynthetic inclusions have been shown to be more beneficial when the ABC layers are relatively thin; moreover, with an increase in the thickness of the ABC, the contribution of the geosynthetic inclusion to the reduction of rut depth development decreases (Fannin and Sigurdsson 1996; Hufenus et al. 2006; Cote et al. 2010; Al-Qadi 2012). The results presented by Cancelli and Montanelli (1999), and Perkins (1999) indicated that the efficiency of geosynthetics reinforcement inclusion is more pronounced with soft subgrade soil. The optimum location of reinforcement layer has also been investigated (e.g. Perkins et al. 1999). Al-Qadi et al. (2012) recommended placing the reinforcement layer at the upper one-third of the ABC layer; however for the thinner ABC layer, the reinforcement should be located at the interface of the ABC and subgrade layer. Abu-Farsakh et al. (2011) reported similar results regarding the optimum location of a single layer of reinforcement; however, it was determined that double reinforcement layers inclusion (i.e., at the upper and lower third of the sample height) led to the largest improvement regardless of the geogrid type. Numerical study by Saad et al. (2006) indicated that the location which provides the highest

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efficiency of reinforcement inclusion, regardless of the subgrade quality, is at the lower one-third of the base thickness. Abu-Farsakh et al. (2011) and Qian et al. (2012) reported that a geogrid with triangular aperture shape provides better improvement compared with the biaxial geogrid with similar tensile moduli.

A set of numerical analyses is performed in this study using PLAXIS 3D software to investigate the optimum location of the reinforcement layer within the ABC layer and provide an insight into the reason for the improvement in performance. Two ABC layer thicknesses are modeled under “stationary” cyclic loading. Various radii of the loaded area are used in the analyses. The subgrade soil and ABC materials properties are defined within the context of the Hardening Soil small-strain (HS small-strain) constitutive models. The numerical model is validated using data from field study reported by Mousavi et al. (2016).

SOIL CONSTITUTIVE MODEL

The Hardening Soil (HS) small strain constitutive model was implemented in this study because of its capability to incorporate the soil stiffness’s nonlinear dependency on the strain level, as well as simulate the stiffness hardening due to an increase in confining pressure. The relationship between axial deviatoric stress and the axial strain was formulated first using the hyperbolic relationship developed by Konder (1963), and later implemented in the constitutive model by Duncan and Chang (1970), as expressed in Equation 1:

$$-\varepsilon_1 = \frac{1}{E_i} \frac{q}{1 - q/q_a} \quad q < q_f \quad (1)$$

where q_a and E_i are defined as Equation 2 and 3:

$$q_a = \frac{q_f}{R_f} \quad (2)$$

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$$E_i = \frac{2E_{50}}{2 - R_f} \quad (3)$$

The E_{50} is the stress dependent stiffness modulus which is given by Equation 4:

$$E_{50} = E_{50}^{ref} \left(\frac{c \cos \varphi - \sigma_3' \sin \varphi}{c \cos \varphi + p^{ref} \sin \varphi} \right)^m \quad (4)$$

The stress dependency of E_{50} is expressed by the power m . The m value is recommended to be between 0.5 for sand and silt and 1.0 for soft clayey soil, (Janbu 1963; Von Soos 1990). Benz (2006) defined the shear stress-shear strain relationship in the context of the HS small-strain model, as expressed in Equation 5:

$$\tau = G_s \gamma = \frac{G_0}{1 + 0.385 \left| \frac{\gamma}{\gamma_{0.7}} \right|} \quad (5)$$

The stress dependency of the shear modulus is given by Equation 6:

$$G_0 = G_0^{ref} \left(\frac{c \cos \varphi - \sigma_3' \sin \varphi}{c \cos \varphi + p^{ref} \sin \varphi} \right)^m \quad (6)$$

INPUT MATERIAL PROPERTIES

ABC and Subgrade Layers

The input materials properties were selected based on laboratory testing results, and numerical model validation using full-scale field testing results presented in Mousavi et al (2016). An ABC Class IV layer thickness of 203 mm (8 in.) was used over geogrid reinforcement to stabilize the soft subgrade during the full-scale testing phase. The in-situ subgrade soils were classified as SM and ML (A-4, A-4a), and MH (A-7-5); these were Piedmont residual soils. The ABC and subgrade soils properties are summarized in Table 1. As will be discussed later, the analyses were performed for two thicknesses of ABC (203 and 305 mm) layer.

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Geosynthetic

The geosynthetic reinforcement was considered a geogrid and modeled as linear elastic materials. The only parameter needed for such representation is the normal elastic stiffness, EA , which is given by Equation 7:

$$EA = \frac{T_{@ \varepsilon \%}}{\varepsilon} \quad (7)$$

Where $T_{@ \varepsilon \%}$ is the axial strength at a given magnitude of strain, $\varepsilon\%$. The EA values of 240 kN/m (16200 lb/ft) at a strain level of 5 percent, was selected for the geogrid reinforcements, as used in the full-scale testing reported by Mousavi et al. (2016). The interface layers are defined for both sides of the geogrid. A reduction factor of 1 (meaning no reduction in the interface strength, or 100% efficiency of the geogrid-backfill interface) was assigned to the interface of the geogrid and ABC and the geogrid and subgrade soil.

LOADING CYCLE

The shape of the applied cyclic loading was captured from Earth Pressure Cell (EPC) that recorded data during the full-scale testing phase of the study, as shown in Fig. 1. The radius of the loaded area was calculated as 147 mm (5.8 inches) corresponding to a tire pressure of 590 kPa (85 psi) and an axle load of 80 kN (18,000 lb). Numerical analysis results reported by Mousavi (2016) indicated that the efficiency of the reinforcement in reducing surface deformation reaches a constant value after 100 load cycles. Therefore, results presented herein for comparative purpose correspond to 100 loading cycles in order to simplify the computational process and render the run time to manageable duration (typical run is about 24 hrs, for 100 load cycles).

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MODEL GEOMETRY

The model domain extended 3048 mm (120 in.) in both the X and Y directions and 4572 mm (180 in.) in the Z direction in order to eliminate the boundary effects and rebounding of the reflected wave into the zone impacted by loading (Howard and Warren 2009). The absorbent boundaries were considered for the $X_{\max}$, $Y_{\max}$, and $Z_{\min}$ planes to absorb stress waves without rebounding into the soil body. A set of the general fixities applied imposed to the boundaries of the numerical model domain, as summarized in Table 2.

In order to eliminate the effect of the size of the generated mesh on the results, the ABC and soft A-4 subgrade soil were divided into three volumes, as shown in Fig. 2. Different combinations of coarseness factors were assigned to the soil volumes until no change in surface deformation under static loading of 590 kPa (85 psi) was obtained. It was determined that maximum computed deformation does not change by utilizing more than 16000 elements in the model geometry. More details on mesh sensitivity analyses can be found on Mousavi et al. (2016).

NUMERICAL ANALYSES RESULTS

Optimum reinforcement location within the ABC layer was investigated for ABC with a thickness (H) of 203 and 305 mm (8, and 12 in.) respectively. The effect of any matric suction was ignored and the surface deformation was computed under loaded areas with a radii (r) of 76, 152, and 305 mm (3, 6, and 12 in.), respectively. The reinforcement layer was located at various depths (D) from the surface, as summarized in Table 3.

Effect of Reinforcement Location

Fig. 4 shows the computed permanent surface deformation of the reinforced sections after 100 load cycles. Data in Fig. 4 are for three loaded areas with radii of 76, 152, and 305 mm,

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respectively, and two ABC thicknesses of 203 and 305 mm. As shown in Fig. 4, the permanent surface deformation of the reinforced section depends on reinforcement depth (D), presented here in terms of the ratio of embedded depth to the radius of loaded (D/r). The results are in good agreement with data presented by Al-Qadi et al. (2012), Abu-Farsakh et al. (2011) Saad et al. (2006). Although these studies recommend an optimum location of the reinforcement layer based on the ABC thickness, no provision was made for the size of the loaded area. The numerical analyses results presented in Fig 4. indicated that the surface deformation for reinforced sections, with the two ABC layer thicknesses, is minimized when the reinforcement layer is placed at $D/r=0.5$. The significance of this ratio, in view of the size of the loaded area, is discussed later.

Fig. 5 shows the surface deformation after 100 load cycles, in terms of D/H ratio. It can be seen that the location which provides the maximum efficiency of the reinforcement inclusion depends on the radius of the loaded area and does not seem to be a function of the ABC layer thickness. It was observed that placing the reinforcement layer at a depth equal to half of the radius of loaded area, as compared to placing it at the interface between the ABC and the subgrade layers, can significantly decrease the surface deformation.

Fig. 6 shows the variation of vertical strain with depth beneath the center of the loaded area, for the unreinforced section, after 100 loaded cycles for ABC layer with a thickness of 203 mm (8 in.). In this case, the maximum vertical strain occurs at the depth that approximately equal half of the radius of the loaded area ($z = 0.5.r$); which is consistent with Schmertmann (1970)'s strain influence diagram under squarely loaded area. Accordingly, it is hypothesized that the reinforcement layer should be placed at the depth corresponding to maximum vertical strain to improve efficiency of the reinforcement contribution.

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Mobilized Tension Force

Variation of mobilized tension force in the reinforcement element with respect to its embedded depth was investigated under each loaded area. Plaxis 3D calculates mobilized tension force in the reinforcement layer in two local directions 1 and 2, based on the deformation in these directions, as demonstrated in Fig. 7 and expressed in Equations 8 and 9:

$$N_1 = EA_1 \varepsilon_1 \quad (8)$$

$$N_2 = EA_2 \varepsilon_2 \quad (9)$$

In this case N_1 , U_1 and N_2 , U_2 are in XX and YY direction respectively. As shown in Figs. 8 (a-b), it was observed that the software does not rotate the local axis (U_1 and U_2) directions as the planes start to deform under the applied load. In this case, the software maintains U_1 and U_2 parallel and equal to U_x and U_y of the reinforcement node, respectively. Accordingly, the computed mobilized force in the geogrid is independent of the vertical deformation (U_z), and is only contingent upon the horizontal deformation in XY plane. Therefore, manual computation of the force in the reinforcement is necessary.

In order to compute the mobilized tension force in the geogrid elements taking into account U_z , the mobilized tension force was hand calculated by using Plaxis U_x and U_z output for each case. Fig. 9(a) shows the diagram of the 2 nodes of one geogrid element, with their U_z , and U_x , deformation in ZZ and XX direction. Fig. 9(b) illustrates how the new element length, L_2 , is calculated based on the relative nodes deformation, as expressed in Equation 10:

$$L_2 = \sqrt{(L_1 + (U_{x2} - U_{x1}))^2 + (U_{z1} - U_{z2})^2} \quad (10)$$

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Equations 11 and 12 formulate in-plane strain of geogrid and mobilized tension force, respectively:

$$\varepsilon = \frac{L2 - L1}{L1} \quad (11)$$

$$F = (EA) \cdot \varepsilon \quad (12)$$

Fig. 10 shows the hand calculated maximum mobilized tension force in geogrid elements after 100 load cycles, as a function of the D/r ratios used in this study. It was observed that greater tension force is mobilized when reinforcement is implemented at the depth where maximum vertical strain occurs. Therefore, this explains the observation that permanent surface deformation is minimized when the reinforcement layer is placed at the depth at which maximum vertical strain occur ($D=0.5r$), with such a depth being a function of the diameter of the loaded area.

Influence of Reinforcement Inclusion

Fig. 11 shows the effectiveness of the reinforcement inclusion in terms of the ratio of D/r, for two thickness of ABC. The effective is represented by efficiency factor (η) which calculated as presented in Equation 13. It was observed that the FEM results are consistent with the literature, which provided improvement with reinforcement is more pronounced with a thinner thickness of ABC (Fannin and Sigurdsson 1996; Hufenus et al. 2006; Cote et al. 2010; Al-Qadi 2012). As shown in Fig. 11, reinforcement inclusion can be ineffective if it is not implemented at the appropriate location. It can be seen that the efficiency of the geogrid can significantly increase from less than 5% to more than 70% if the reinforcement is located at the proposed optimum location of $D/r=0.5$.

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$$\text{Efficiency: } \eta = \frac{\delta_{unreinforced} - \delta_{reinforced}}{\delta_{unreinforced}} \quad (13)$$

CONCLUSIONS

Numerical analyses were performed using Plaxis 3D and cyclic loading to evaluate the optimum location of a reinforcement layer such that the efficiency of the reinforcement inclusion is improved in an unpaved road section. The analyses results are also used to explain a key factor for improvement of performance. Based on the analyses results, the following conclusions can be drawn:

- Regardless of the ABC layer thickness, the surface deformation is minimized when the reinforcement is embedded at a depth of about half of the radius of loaded area, ($D/r = 0.5$).
- The inclusion of reinforcement can lead to even smaller surface deformation if it is placed at the depth at which maximum vertical strain occurs. This is especially important in cases with larger ABC thickness where the reinforcement is conventionally located at the interface of the base and subgrade layers.
- Computed mobilized force in geogrid in Plaxis 3D, under vertical load, seems to be incorrect as the force is computed independent of the vertical deformation. Vertical deformation is a main component that along with horizontal deformation (in XY plane) define the deformed shape of the geogrid layer and therefore mobilizes force.
- A higher tension force is mobilized in reinforcement elements when the layer is placed at a depth corresponding to the maximum vertical strain (in this paper it was at $D = 0.5r$). Thus reinforcement inclusion is more beneficial in the reduction of permanent surface deformation.

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- The numerical analyses results confirmed data in literature indicating that reinforcement produces a higher reduction in surface deformation with thinner ABC layer. However, the additional finding of higher efficiency of reinforcement contribution when the layer is placed at $D/r=0.5$ further explains that the issue is more related to the location of the reinforcement layer rather than to the mere ABC layer thickness.

LIST OF NOTATIONS

m : Stress-dependent stiffness according to a power law.

E_{50}^{ref} : plastic straining due to primary deviatoric loading at 50% strength, at reference pressure

E_{oed}^{ref} : Plastic straining due to primary compression, at reference pressure

E_{ur}^{ref} : elastic unloading/reloading, at reference pressure

ν_{ur} : unloading/reloading Poisson's ratio

G_0 : initial shear modulus.

G_s : secant shear modulus

$\gamma_{0.7}$: shear strain level at which the G_s is reduced to 70 percent of the G_0 value

q_f : ultimate deviatoric stress

R_f : failure ratio

c : cohesion

σ'_3 : effective confining pressure

ϕ : friction angle

p^{ref} : reference pressure (etc, 1 atm = 100 kPa)

S_u : undrained shear strength

EA: normal elastic stiffness

U_i : deformation in direction i

D : reinforcement embedded depth

r : radius of the loaded area

δ_z : surface deformation

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H: thickness of aggregate base course

Ni: mobilized force in reinforcement in direction i

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Figure Captions

Figure 1. One applied load cycle.

Figure 2. Model geometry and soil volumes.

Figure 3. Location of the reinforcement layer.

Figure 4. Surface deformation vs D/r .

Figure 5. Surface deformation vs D/H .

Figure 6. Vertical strain distribution with depth after 100 load cycles, under center of loaded area for unreinforced unpaved section with H : 203 mm.

Figure 7. Local force, deformation and strain axis (After Plaxis 3D).

Figure 8. (a) U_x , (b) U_1 , of geogrid after 100 load cycles; H , D , and $r=305$ mm, legends are in inches (1 in. =25.4 mm).

Figure 9. (a) Deformed geogrid nodes, (b) relative deformation of geogrid nodes.

Figure 10. Maximum mobilized tension force in the geogrid after 100 load cycles.

Figure 11. Influence of reinforcement inclusion.

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Table 1. ABC and Subgrade Soils Properties Used in Numerical Analyses.

Material	Thickness (mm)	γ_{mist} (kN/m ³)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} ² (MPa)	m	ν_{ur}	G_0^{ref} (ksi)	$\gamma_{0.7}$ (%)	ϕ'	c'/s _u (kPa)	R _f
ABC	-	23	200	180	400	0.64	0.2	800	0.05	43	0	0.9
A-4	610	20	75	75	150	0.5	0.2	360	0.001	25	13.8	0.9
A-7-5	3760	19	48	24	150	1	0.2	550	0.003	NA	193	0.9

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Table 2. Geometry Boundary Conditions.

Plane	Deformation fixities	Deformation
X min	Normally fixed	$U_x=0$
X max	Normally fixed	$U_x=0$
Y min	Normally fixed	$U_y=0$
Y max	Normally fixed	$U_y=0$
Z min (bottom)	Fully fixed	$U_x=U_y=U_z=0$
Z max (surface)	Free	free

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Table 3. Reinforcement depth.

H (mm)	r (mm)			D/H		
203	76	1	0.69	0.31	0.08	0.19
	152	1	0.69	0.31	0.13	
	305	1	0.69	0.31		
305	76	1	0.50	0.33	0.13	0.05
	152	1	0.67	0.25	0.13	
	305	1	0.75	0.50	0.25	

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