NUMERICAL INVESTIGATION OF GEOSYNTHETIC REINFORCED SOIL MASS WITH BLOCK FACING AND CLOSELY-SPACED REINFORCEMENTS

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Abstract. Bridge abutments using geosynthetic reinforced soil (GRS) for direct supporting of the deck is a solution with significant advantages over conventional systems. Among the main characteristics of this type of structure, the small reinforcement spacing, frequently lower than 0.3 m, requires attention. This paper provides an investigation to assess the effect of closely-spaced reinforcements on the behavior of a GRS mass using block facing, and subjected to a uniformly distributed loading with typical value of service conditions. The Plaxis 2D finite element software was used to conduct a parametric study to investigate the influence of vertical spacing (S_v) and reinforcement stiffness (J). The numerical investigations were developed according to different approaches to analyze the effect of vertical spacing. Initially, combinations of S_v and J were adopted without considering a constant J/S_v ratio and then the J/S_v ratio was kept constant. The results indicated a significant effect of vertical spacing for both approaches. The maximum lateral displacements of the facing and soil settlements near facing were found to decrease. This behavior was obtained for all the values adopted for the constant J/S_v ratio.

Keywords: Geosynthetic; Reinforced Soil; Vertical Spacing; Lateral Displacement; Settlements; Deformations; Bridge Abutment.

1 Introduction

Geosynthetic reinforced soil (GRS) are retaining structures composed of layers of compacted soil reinforced with geosynthetics, to increase the soil's mechanical tensile strength and retain it. This type of structure is becoming common in bridge abutments. The main reasons for selecting this technique relates to a global economy to the cost of the project and a reduction to complete elimination of "bridge bumps" at approaching embankments.

An advanced technique to the GRS is the Geosynthetic Reinforced Soil - Integrated Bridge System (GRS-IBS), developed by the Federal Highway Administration (FHWA) (Adams et al. [1]; Adams et al. [2]). In this technique, the bridge is placed directly on the approaching embankment with GRS, without any other structural joints between the structures. Adams et al. [1] explain that the GRS-IBS consists of alternating thin layers of compacted soil and geosynthetic reinforcement, of about 30 cm in height. The soil and the geosynthetics act as a composite, providing the bearing capacity needed for the superstructure of the bridges. The reinforcements act as the means to provide reduction and restriction to lateral displacements of the soil, improve the strength to stresses from compaction and overburden, and more. These noted benefits may be linked to a greater interaction between the soil and the geosynthetic in the thinner layers (Adams et al. [1]; Wu [3]).

Most of the design methods developed to date (Elias, Barry e Christopher [4]; AASTHO [5]) are based on the method of limit equilibrium. In this method, the tensile strength mobilized in the reinforcement (T) is directly influenced by the vertical spacing (S_v) and by the effective horizontal stresses acting on the system (σ_h). Basically, this methodology supposes that greater spacing may be totally compensated by the use of stronger reinforcements, as long as these parameters (S_v and T) increase with the same proportion (i.e., the T/S_v ratio remains constant). Therefore, the soil-geosynthetic interaction is not properly addressed in this methodology, and the behavior of the composite is not satisfactory predicted.

Recent studies using smaller vertical spacing indicated that the spacing is more important in the behavior of the GRS than expected. For instance, Nicks et al. [6], using Performance Tests (PT), kept the constant T/S_v ratio for all samples. They concluded that by increasing the vertical spacing and decreasing the tensile strength of the reinforcement at the same proportion reduced the bearing capacity of the GRS. Nicks, Esmaili e Adams [7] investigated the response of the PT conducted by Nicks et al. [6] to vertical and lateral displacements for normal service condition (200 kPa) and rupture (400 kPa). The samples with smaller spacing and lower tensile strength showed smaller vertical displacements than the samples with greater spacing and tensile strength, in a constant T/S_v ratio.

Another approach to investigate the effect of vertical spacing on the behavior of GRS walls is through the analysis of the reinforcement stiffness (J). For geosynthetics with a linear stress-strain behavior, and with the mobilized strength proportional to the reinforcement stiffness, it is adequate to use the J/S_v ratio to investigate the impact of S_v under typical working load conditions.

Shen et al. [8] used this approach in numerical analysis using the software FLAC2D e FLAC3D. They investigated PT in parametric studies keeping the constant J/S_v ratio. The authors observed that by increasing the vertical spacing and the reinforcement stiffness in the same proportion, the bearing capacity of a mini-pier of GRS reduced considerably. Abu-Farsakh, Ardah e Voyiadjis [9] also investigated the effect of keeping J/S_v constant in numerical analyses of GRS-IBS using Plaxis 2D. Based on a parametric study, the authors observed that the spacing between reinforcements is more relevant than the reinforcement stiffness on the behavior of GRS-IBS, for spacing equal or greater than 0.2 m.

In this paper, a numerical analysis was developed to investigate the influence of lower vertical spacing on the behavior of a GRS structure with block facing under a uniformly distributed vertical load. The applied load is representative of typical values for service conditions of bridge and overpass abutments. The models were developed based on the work of Ardah et al. [10]. Parametric analyses were conducted to investigate the effect of vertical spacing and reinforcement stiffness, separately. Moreover, the effect of various combinations of vertical spacing and reinforcement stiffness, in a constant J/S_v ratio, on a GRS mass were also analyzed.

2 Numerical Modelling

2.1 Overview of the numerical models

The software Plaxis 2D 2016 was used to simulate the behavior of a GRS mass with concrete block facing, under a uniform vertical load in plane strain. The models are based on the study of Ardah et al. [10], simulating the behavior of a bridge abutment in GRS-IBS under working loads. The cross-section and the loading conditions were simplified, compared to the models of Ardah et al. [10], to fit the conditions established in this study. The finite elements used to model each of the GRS mass components, the constitutive models, and the main parameters used were kept the same as Ardah et al. [10].

2.2 Constitutive models, meshing and boundary conditions

The soil was represented by the Hardening Soil (HS) constitutive model, with the same parameters used in the calibration model of Ardah et al. [10]. It is a hyperbolic elastoplastic model with hardening after unloading and subsequent reloading. The geosynthetic reinforcements were represented by a linear elastic model, with the elements designated by the software Geogrid. The concrete blocks of the facing were represented by a linear elastic model with dimensions of 0.2 m x 0.2 m. The reinforcements were connected to the facing by inserting the geosynthetic between two blocks with an overlap of 100% of the width of the block.

Various types of interfaces were used to model the shear strength between elements. These interfaces were represented by "joint" elements already available in the software. These elements use a linear elastic model with Mohr-Coulomb failure criterion. A factor of reduction in the strength (R_{inter}) was used for the block-soil and geosynthetic-soil interfaces. In this case, the strength and stiffness are calculated based on the parameters of the related soil. The values of the parameters of the soil, reinforcement, blocks and interfaces are shown in Table 1.

Table 1. Material properties of components in modelling of the geosynthetic reinforced mass

Model components	Constitutive Model	Input Parameters
Backfill	Hardening Soil	Unit weight (γ) = 18 kN/m^3
		Modulus from triaxial test (E_{50}^{ref}) = 34,000 kPa
		Modulus from oedometer test (E_{oed}^{ref}) = 140,000 kPa
		Unloading/reloading modulus (E_{ur}^{ref}) = 480,000 kPa
		Poisson's ratio (ν) = 0.2
		Cohesion (c) = 20 kPa
		Friction angle (ϕ) = 51°
		Dilatancy angle (ψ) = 21°
Geotextile reinforcement	Elastic Linear	Axial stiffness (EA)[1] = 150 kN/m; 300 kN/m; 600 kN/m; 1200 kN/m
Facing block	Elastic Linear	Unit weight (γ) = 12.5 kN/m^3
		Young's modulus (E) = 3 × 10^7 kPa
		Poisson's ratio (ν) = 0
Interfaces		
Geotextile – soil	Mohr-Coulomb	R_{inter} = 0.8
Block – soil	Mohr-Coulomb	R_{inter} = 0.65
Block – block	Mohr-Coulomb	Cohesion (c) = 1kN/m²
		Friction angle (ϕ) = 31°
Block – Geotextile	Mohr-Coulomb	Cohesion (c) = 7kN/m²
		Friction angle (ϕ) = 34°

(1) The adopted values varied in the parametric study.

The numerical analyses were developed using Plaxis 2D in plane strain. A previous study of the refinement of the mesh was carried out. It was noticed that the maximum software refinement did not cause significant differences in the results or in the processing time. Therefore, a dense finite element mesh composed by triangular elements with 15 nodes was adopted. The lower boundary was fixed for horizontal and vertical movements. At the right face, the horizontal movements were restrained, but vertical movements were allowed. At the left face, the horizontal and vertical movements were initially restrained during construction and, after construction and during the simulation of applying the surcharge, it was allowed to move in all directions.

The number of reinforcement layers followed a fixed proportion. That is, by folding S_v, for example half the anterior number of layers was obtained. Thus, the minimum height of the SRG mass that allowed this type of configuration was 1.4m, adopted in this study. Regarding the length of the reinforcements, Adams et al. [2] recommend a minimum value of 70% of the height of the wall, then a length equal to 2.0 m was used. Figures 1a and 1b show the mesh, boundary conditions and overall assembly of the model for S_v equals 0.2 m and 0.4 m, respectively.

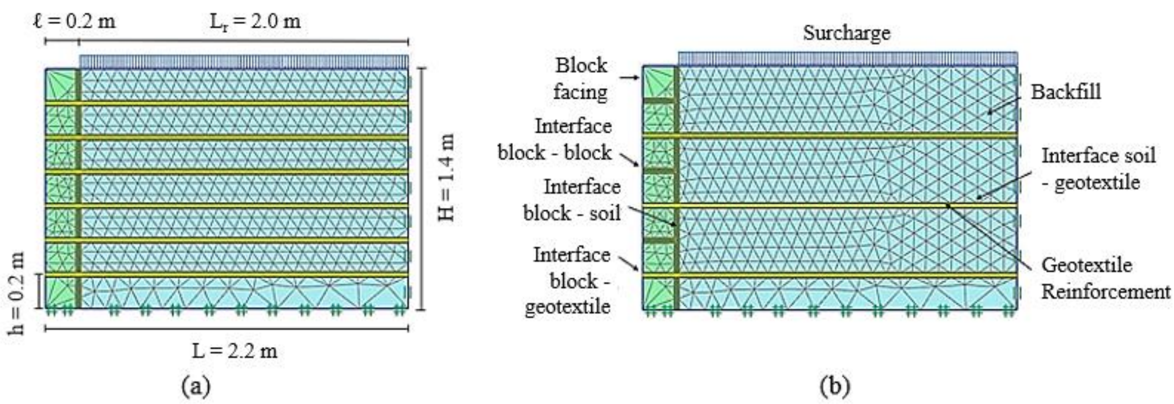

Figure 1. Finite element mesh and boundary conditions of the GRS mass: a) Configuration with S_v = 0.2 m; b) Configuration with S_v = 0.4 m

The GRS mass was divided into layers to simulate the construction process in stages. Plaxis 2D has built-in features that allow for this procedure.

3 Parametric study

A parametric study was developed to investigate the influence of small vertical spacing on the behavior of GRS masses with concrete block facing. The models were developed to investigate the separate effects of vertical spacing and reinforcement stiffness and the combined effect of these two parameters in various values keeping the constant J/S_v ratio. A uniformly distributed load of 200 kPa was applied to simulate the typical working conditions in bridge and overpass abutments. After construction, this surcharge was applied in equal increments of 50 kPa until reaching the 200 kPa.

The vertical spacing investigated in the parametric study were 0.2 m and 0.4 m. The reinforcement stiffness investigated were 150 kN/m, 300 kN/m, 600 kN/m and 1200 kN/m. The J/S_v ratio applied were 750 kN/m/m, 1500 kN/m/m e 3000 kN/m/m, based on the combination of J and S_v adopted in this study.

The number of layers was selected based on a fixed proportion. For a value of S_v twice as big, the number of layers were half of the previous S_v. Thus, the minimum height of the GRS wall for this study was 1.4 m.

4 Results and discussion

4.1 Effect of small values of vertical spacing - J/S_v ratio not constant

The influence of S_v and J in the lateral displacement may be investigated by varying the reinforcement stiffness or the vertical spacing solely. From the results presented in Table 2 and Table 3, it is observed that the spacing shows a greater influence in the lateral displacement than the reinforcement stiffness. For instance, for a constant value of S_v, but a J with double the value, the lateral displacement (δ_{hmax}) reduces by approximately 26% (Table 2). For a constant J, but an S_v reduced in half, δ_{hmax} reduces by approximately 48% for J = 300 kN/m and 50.5% for J = 600 kN/m (Table 3).

Table 2. Effect of stiffness on maximum lateral displacement (δ_{hmax}) and settlement (δ_v) under surcharge of 200kPa (normal service condition)

S_{v1} (m)	J_1 (kN/m)	J_2 (kN/m)	J_3 (kN/m)	δ_{hmax} Decrease (1) (%)		δ_v Decrease (2) (%)	
				$J_1 - J_2$	$J_2 - J_3$	$J_1 - J_2$	$J_2 - J_3$
0.20	300	600	1200	29.4	32.7	9.6	13.5
0.40	300	600	1200	25.6	26.4	14.0	12.3

(1) Reduction of δ_{hmax} when varying stiffness from J_1 to J_2 and from J_2 to J_3.
(2) Reduction of δ_v of the reinforced soil on the face by varying the stiffness J_1 to J_2 and from J_2 to J_3.

Table 3. Effect of vertical spacing on maximum lateral displacement (δ_{hmax}) and settlement (δ_v) under surcharge of 200kPa (normal service condition)

J (kN/m)	**S_{v1} (m)**	**S_{v2} (m)**	**δ_{hmax} Decrease (1) (%)** $S_{v1} - S_{v2}$	**δ_v Decrease (2) (%)** $S_{v1} - S_{v2}$
300	0.4	0.2	47.9	27.4
600	0.4	0.2	50.5	23.8
1200	0.4	0.2	54.8	25.0

(1) Reduction of δ_{hmax} by varying the spacing from S_{v1} to S_{v2}
(2) Reduction of δ_v of the reinforced soil on the face by varying the spacing from S_{v1} to S_{v2}

As for the settlement of the soil in the facing, the same effect is observed, where the vertical spacing influences more than the reinforcement stiffness. For a constant S_v, but a doubled J, δ_v reduces by 14% for J = 300 kN/m and 12.3% for J = 600 kN/m, as shown in Table 2. Table 3 shows that for a constant value of J, but S_v reduced in half, δ_v reduces in 27.4% and 23.8% for J = 300 kN/m and J = 600 kN/m, respectively.

4.2 Effect of small values of vertical spacing - constant J/S_v ratio

The combination of different reinforcement stiffness and vertical spacing values was investigated to study the GRS masses with various vertical spacing, but constant J/S_v ratio. For this analysis, three constant J/S_v ratios of 3000 kN/m/m, 1500 kN/m/m and 750 kN/m/m were investigated.

The results show that, for all three cases, the maximum lateral displacement of the facing, during the loading stages, happens at the surface of the GRS wall. As expected, δ_{hmax} increases with the increase of the surcharge. Table 4 shows the values of lateral displacement at the top of the facing and the settlement of the soil adjacent to the facing, for all three cases, for the maximum surcharge of 200 kPa. The results show that varying the values of the J/S_v ratio impact the horizontal and vertical displacement of the soil of the GRS. For smaller J/S_v ratios, the lateral displacement and settlements observed are greater.

Table 4. Maximum lateral displacement (δ_{hmax}) and settlement (δ_v) values of the reinforced soil on the face under an surcharge of 200 kPa (normal service condition)

J/S_v (kN/m/m)	**S_v (m)**	**J (kN/m)**	**δ_{hmax} (mm)**	**δ_{hmax}/H (%)**	**δ_v (mm)**	**δ_v/H (%)**
3000	0.4	1200	5.26	0.38	9.28	0.66
	0.2	600	3.54	0.25	8.05	0.58
1500	0.4	600	7.15	0.51	10.58	0.76
	0.2	300	5.01	0.36	8.91	0.64
750	0.4	300	9.61	0.69	12.29	0.88
	0.2	150	6.75	0.48	10.58	0.76

The guidelines of FHWA (Adams et al. [1]) for GRS masses in bridge abutments specify that for service conditions, the lateral strain (ε_h) must be limited to 1% of the total height of the GRS wall (H). For all cases investigated in this research, the maximum lateral strain is observed for the surcharge of 200 kPa. All maximum lateral strains found (Table 4) are inferior to the recommended by FHWA.

Furthermore, the impact of the vertical spacing in the reduction of δ_{hmax} is slightly greater for J/S_v = 3000 kN/m/m than the other values for a constant ratio of J/S_v. The maximum reduction is 32.7% for 200 kPa when the vertical spacing and reinforcement stiffness are reduced in half, as shown in Table 5.

Tabela 5. Effect of closely-spaced on maximum lateral displacement (δ_{hmax}) and face settlement (δ_v) for models with constant J/S_v under surcharge of 200 kPa (normal service condition)

J/S_v (kN/m/m)	Condition 1		Condition 2		δ_{hmax} Decrease [1] (%)	δ_v Decrease [2] (%)
	S_{v1} (m)	J_1 (kN/m)	S_{v2} (m)	J_2 (kN/m)	1 – 2	1 – 2
3000	0.40	1200	0.20	600	32.7	13.3
1500	0.40	600	0.20	300	29.9	15.7
750	0.40	300	0.20	150	29.8	13.9

(1) Reduction of δ_{hmax} when varying from condition 1 to condition 2

(2) Reduction of δ_v of the reinforced soil on the face when varying from condition 1 to condition 2

Regarding the settlement of the soil in the face of the reinforced soil wall, Table 4 shows that it decreases when the spacing and the stiffness are reduced in half. This behavior is observed in all cases for constant J/S_v ratios, but it is slightly greater for J/S_v = 1500 kN/m/m. In this case, the reduction in the settlement is 15.7%.

The contour of the ground settlement of the GRS under a load of 200 kPa is shown in Figures 2a, 2b and 2c, for J/S_v equal to 3000kN/m/m, 1500kN/m/m and 750kN/m/m, respectively. The x-axis is the horizontal distance from the facing normalized by the length of the geosynthetic reinforcement (L_r). The y-axis is the vertical settlement normalized by the total height of the GRS wall. It is observed that a reduction on the vertical spacing and on the reinforcement stiffness in the same proportion reduces the ground settlement up to a distance of X/L_r = 0.4, but more significantly up to X/L_r = 0.2.

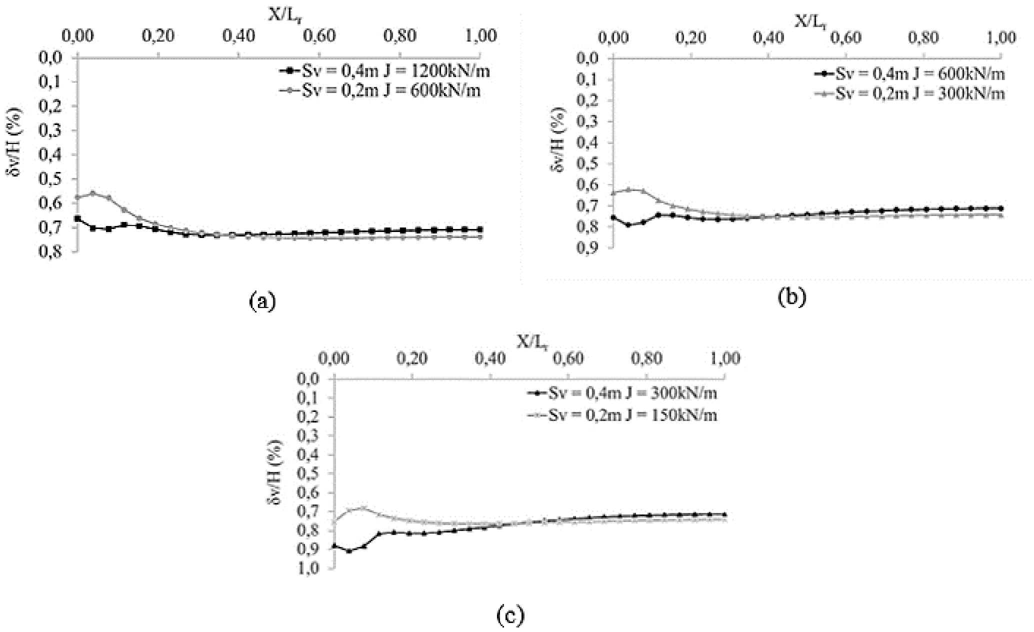

Figure 2. Surface settlement of the GRS mass: (a) J/Sv = 3000 kN/m/m (b) J/Sv = 1500 kN/m/m (c) J/Sv = 750 kN/m/m

It is important to note that there is a distinct response of the surface settlement with the distance of the facing. The lower values are found closer to the facing than at a greater distance ($X/L_r \geq 0.4$), especially for smaller vertical spacing. This effect is even more pronounced with an increase in reinforcement stiffness. In other words, for larger spacing, but with a stiffer geosynthetic (S_v = 0.4 m e J = 1200 kN/m), the vertical settlement of the surface closer to the facing is also considerably small.

Other factors may also influence the results of the vertical spacing and restriction of the settlements close to the GRS facing, such as: i) shear strength of interface block-soil; ii) rotation of the direction of the reinforcement at the facing; iii) rotation of the blocks of the facing due to the absence of foundation soils. These factors, along with the smaller spacing of the reinforcement, may justify the ground settlement contour pattern seen in Figure 2.

5 Conclusions

A parametric study was performed to investigate the effect of small vertical spacing between reinforcements in the performance of a geosynthetic reinforced soil (GRS) mass subjected to uniformly distributed surcharge under working condition of bridge abutments using the finite element numerical method. The numerical model was developed based on the work of Ardah et al. [10]. The parameters included in this study are the impact of vertical spacing (S_v) and reinforcement stiffness (J), both separately and in combinations of S_v and J, keeping the constant J/S_v ratio. Based on the results, the following results are drawn:

- The vertical spacing between the reinforcements shows a greater impact on the performance of the GRS mass than the reinforcement stiffness. For both approaches adopted in this research, smaller S_v results in smaller maximum lateral displacement and surface settlements of the soil adjacent to the facing. This behavior is observed for various values of constant J/S_v ratio.
- The contours of surface settlement of the GRS soil shows smaller vertical displacement closer to the facing and greater farther from the facing, especially for smaller S_v and higher J. However, this impact is only observed up to a distance of 40% of the length of the reinforcement, from the facing. The most expressive response is obtained up to $X/L_r = 0.2$. These results suggest that the behavior of vertical settlement, using smaller spacing, depends on the characteristics of the face and the foundation soil.

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