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Technical note

Modeling of the compaction-induced stress on reinforced soil walls

S.H. Mirmoradi*, M. Ehrlich

Dept. of Civil Engineering, COPPE, Federal University of Rio de Janeiro, UFRJ, RJ 21945-970, Brazil

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ABSTRACT

A new simple analytical procedure (AASHTO modified) that includes the effect of the induced stress due to backfill compaction for use with conventional design methods of geosynthetic reinforced soil (GRS) walls is proposed. The proposed analytical procedure may be used with any conventional design methods that do not take into consideration the effect of the compaction-induced stress in their calculations. This approach is based on an equation suggested by Wu and Pham (2010) to calculate the increase in lateral stress in a reinforced soil mass due to compaction. Additionally, two numerical procedures for modeling of compaction are described. Analyses using these procedures were performed to evaluate the capability of the proposed analytical procedure. The results were compared with values predicted using the Ehrlich and Mitchell (1994) method, the modified version of the *K*-stiffness method (Bathurst et al., 2008) and the AASHTO simplified method. The results show that the AASHTO modified method and the numerical analyses, in which the compaction-induced stress was modeled using two distributed loads at the top and bottom of each soil layer, resulted in values of the maximum reinforcement tension, T_{max}, that agree with those from the full-scale test and those calculated by Ehrlich and Mitchell (1994). On the other hand, the *K*-stiffness method under-predicts the measured T_{max} values. Moreover, numerical modeling of compaction using a distribution load only at the top of each soil layer overestimated the measurements.

1. Introduction

The importance of backfill soil compaction on the behavior of geosynthetic reinforced soil (GRS) walls has been demonstrated by a number of laboratory and case studies (Ehrlich and Mitchell, 1994; Bathurst et al., 2009; Ehrlich et al., 2012). Compaction promotes displacement during the construction period and reduces both settlement and horizontal displacement due to surcharge load application after construction. In other words, compaction may lead the reinforced soil mass to exhibit a kind of over-consolidation that promotes a stiffer behavior after construction. Additionally, compaction may be the major contributor to reinforcement tension at shallow depths (Ehrlich and Mitchell, 1994, 1995; Ehrlich et al., 2012; Mirmoradi and Ehrlich, 2014b).

However, in most of the current design methods for GRS walls, the effect of the compaction-induced stress is not explicitly taken into consideration (e.g., the AASHTO, 2012 simplified method). Ehrlich and Mitchell (1994) presented an analytical procedure for the internal design of reinforced soil walls that was based on working stress conditions. This method explicitly takes into account the effect of compaction-induced stress, reinforcement, and soil stiffness properties. Comparison of the predicted results using this method showed good agreement with measured reinforcement tension data for several full-scale walls containing a range of reinforcement types.

In recent decades, several numerical analyses using the finite element method (FEM) or finite difference method (FDM) codes have been undertaken to consider the different geometries and parameters in GRS walls. Examples are reported by Hermann and Al-Yassin (1978), Naylor (1978), Ho and Rowe (1997), Rowe and Ho (1998), Helwany et al. (1999), Ling and Leshchinsky (2003), Hatami and Bathurst (2005), Guler et al. (2007), and Mirmoradi and Ehrlich (2013), among others. However, the effect of backfill soil compaction has rarely been considered. Hatami and Bathurst (2005) and Guler et al. (2007) numerically considered the effect of the induced stress due to backfill compaction using FDM (finite difference-based fast Lagrangian analysis of continua program; Itasca Consulting Group, 2001) and FEM (PLAXIS). In both studies, the compaction-induced stresses were modeled using a uniform

* Corresponding author.
E-mail addresses: sh.mirmoradi@gmail.com (S.H. Mirmoradi), me@coc.ufrj.br (M. Ehrlich).

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vertical stress applied only to the top of each backfill soil layer as the wall was modeled from the bottom up. Ehrlich and Mirmoradi (2013), Mirmoradi and Ehrlich (2014a,b) and Riccio et al. (2014) simulated the compaction-induced stress by applying an equal distribution load at the top and bottom of each soil layer. This approach is based on the procedure used by Dantas (2004) and Morrison et al. (2006) for the consideration of the induced stress due to backfill soil compaction.

The objective of the present study is to propose a simple analytical method (AASHTO modified) for the determination of T_{max} that includes the effect of backfill soil compaction. The proposed procedure is based on that suggested by Wu and Pham (2010). The results using the proposed procedure are compared with the results of the numerical modeling using the two compaction procedures as discussed above, the AASHTO (2012) simplified method, the Ehrlich and Mitchell (1994) method and the modified version of *K*-stiffness method (Bathurst et al., 2008).

2. Analytical compaction modeling

Ehrlich and Mitchell (1994) suggested a procedure for the internal design of reinforced soil walls that explicitly takes into account the effect of the induced stress due to backfill compaction. Nevertheless, conventional designs of reinforced soil walls usually do not take into consideration the effect of the compaction-induced stress in their calculations. A new simple procedure that includes the effect of the induced stress due to backfill compaction for use with any conventional design methods is described, as follows.

For the compacted backfill soil, the value of the maximum tension in the reinforcement may be determined by:

$$T_{max} = T_{max,g} + T_{max,c} \tag{1}$$

where $T_{max,g}$ and $T_{max,c}$ represent the values of the maximum mobilized tension in the reinforcement due to geostatic stress and compaction-induced stress, respectively. $T_{max,g}$ corresponds to the tension of reinforcement due to geostatic stress, and it may be calculated using any conventional design method that does not take into consideration the effect of the compaction-induced stress on determination. Based on the AASHTO (2012) simplified method, for example, the value of the maximum tensile stress in the reinforcement is determined by using the following equations:

$$T_{max,g} = KS_v(\gamma z + q) \tag{2}$$

wherez is the depth of the reinforcement layer under the crest of the wall, γ is the soil unit weight, S_v is the vertical reinforcement spacing, q is the surcharge pressure, and K is the active earth pressure coefficient, as determined by:

$$K = \frac{\cos^2(\varnothing + \omega)}{\cos^2\omega(1 + (\sin\varnothing/\cos\omega))^2} \tag{3}$$

where $\varnothing$ and ω are the peak friction angle of the soil and the facing inclination from vertical, respectively.

Note that the use of the AASHTO (2012) simplified method for $T_{max,g}$ determination may be reasonable for situations where there is enough lateral strain mobilization in the reinforced soil mass to reach soil plastic condition (K_a condition); that hypothesis may be considered for typical polymeric reinforcements.

The increase of the value of the maximum mobilized tension in the reinforcement due to the induced stresses due to backfill compaction, $T_{max,c}$, is determined by:

$$T_{max,c} = \Delta\sigma'_{h,c}S_v \tag{4}$$

where $\Delta\sigma'_{h,c}$ and S_v are the increases in effective lateral stress due to backfill compaction and the vertical reinforcement spacing, respectively. A procedure was suggested by Wu and Pham (2010) for calculating the increase in lateral stress in a reinforced soil mass due to compaction:

$$\Delta\sigma'_{h,c} = \Delta\sigma'_{v,c\,max}K_{i,c}F\left[1 + \frac{0.7E_r}{E_sS_v - 0.7E_r}\right] \tag{5}$$

where $\Delta\sigma'_{v,c\,max}$, $K_{i,c}$, E_s, E_r, and S_v are the maximum increases in effective vertical stress due to backfill compaction, lateral earth pressure coefficient, soil stiffness, reinforcement stiffness, and reinforcement spacing, respectively. The value of F can be calculated based on Seed (1983) and Ehrlich and Mitchell (1994) according to

$$F = 1 - \frac{OCR - OCR^{\sin\varphi}}{OCR - 1} \tag{6}$$

where OCR and φ are the over-consolidation ratio and internal friction angle, respectively.

$$\begin{cases} OCR = \sigma'_{zc,i}/\sigma'_z; & \sigma'_{zc,i} > \sigma'_z \\ OCR = 1; & \sigma'_{zc,i} \le \sigma'_z \end{cases} \tag{7}$$

where σ'_z is the effective vertical stress on each layer at the end of construction. The compacted soil layers are relatively thin, thus it may be assumed that all points in the backfill soil layers are driven to the same vertical induced stress, $\sigma'_{zc,i}$, due to compaction. Therefore, the value of the maximum increase in the vertical stress due to compaction in each depth may be calculated as follows:

$$\begin{cases} \sigma'_{v,c\,max} = \sigma'_{zc,i} - \gamma' z; & \sigma'_{zc,i} > \gamma' z \\ \sigma'_{v,c\,max} = 0; & \sigma'_{zc,i} \le \gamma' z \end{cases} \tag{8}$$

Wu and Pham (2010) suggested the Westergaard solution (1938) for calculating the maximum increase in the vertical stress due to backfill compaction. Fig. 1 shows a comparison of the increase in the lateral stress due to backfill soil compaction in a reinforced soil mass presented by Pham (2009) and Wu and Pham (2010) and results based on the mentioned approach (Eq. (8)), assuming that $K_{i,c}$ is equal to the active Rankine condition, K_a. As previously discussed, the use of the active condition (K_a) may be considered reasonable for soils reinforced with conventional polymeric reinforcements. The results are related to a 6 m high GRS mass for five different values of the vertical maximum pressures due to compaction (44, 100, 200, 300, and 500 kPa). Fig. 1 shows that the results determined by the two procedures differ significantly. It is also notable that the increase in lateral stress determined using Eq. (8) would approach zero at compaction influence depth, Z_c, that is a larger depth compared with the results of Pham (2009) and Wu and Pham (2010) and this discrepancy would be greater for the higher value of $\sigma'_{zc,i}$. The compaction influence depth Z_c, is defined as follows (Ehrlich and Mitchell, 1994):

$$Z_c = \frac{\sigma'_{zc,i}}{\gamma} \tag{9}$$

where $\sigma'_{zc,i}$ and γ are the vertical stresses induced during compaction and the soil unit weight, respectively. Note that zero increase of lateral stress (for $Z > Z_c$) means that the geostatic stress overcomes the induced stress due to compaction and the effect of compaction is no longer felt by the soil.