Numerical investigations of GRS wall performance with tiered configurations

Investigações numéricas do desempenho de muros GRS com configurações em níveis

Investigaciones numéricas sobre el comportamiento de los muros GRS con configuraciones escalonadas

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ABSTRACT
Geosynthetic Reinforced Soil (GRS) walls have become increasingly popular as a result of their numerous advantages. In some cases these structures are constructed in a multi-tiered configuration, which makes their behavior more complicated. Nevertheless, the response of the multi-tiered walls is insufficiently explained by the existing design manuals and literature studies. This paper investigated the performance of GRS walls with multi-tiered configurations using two-dimensional (2D) finite element numerical models. This study compares the performance of two-tiered GRS walls with simple GRS walls (single-tiered). It also examines the impact of offset distance, backfill strength properties, and reinforcement parameters (vertical spacing and reinforcement length) on horizontal deformations and reinforcement tensile loads in two-tiered GRS walls. Adopting a multi-tiered configuration for GRS walls can significantly reduce both the horizontal wall deformation and the maximum reinforcement tensile loads. Additionally, the critical offset distance found in this study is significantly smaller.
than that recommended by the Federal Highway Administration (FHWA) guidelines. The finite element results also demonstrate that using high-quality backfill soil can minimize interaction between lower and upper tiers. Using a uniform reinforcement length of 0.6H for both tiers significantly reduces horizontal deformation compared to the FHWA recommendation of 0.6H and 0.35H for the lower and the upper tier respectively.

**Keywords:** Geosynthetics. Multi-Tiered Wall. Offset Distance. Tensile Load. Wall Displacement.

**RESUMO**
Paredes de Solo Reforçado com Geossintéticos (GRS) têm se tornado cada vez mais populares devido às suas inúmeras vantagens. Em alguns casos, essas estruturas são construídas em uma configuração multi-nível, o que torna seu comportamento mais complexo. No entanto, a resposta das paredes multi-nível ainda não é suficientemente explicada pelos manuais de projeto existentes e pelos estudos na literatura. Este trabalho investigou o desempenho de paredes GRS com configurações multi-nível utilizando modelos numéricos de elementos finitos bidimensionais (2D). O estudo comparou o desempenho de paredes GRS de dois níveis com paredes simples de um nível. Além disso, examinou o impacto da distância de deslocamento, das propriedades do material de enchimento e dos parâmetros de reforço (espaçamento vertical e comprimento de reforço) nas deformações horizontais e nas cargas de tração do reforço em paredes GRS de dois níveis. A adoção de uma configuração multi-nível para paredes GRS pode reduzir significativamente tanto a deformação horizontal quanto as cargas máximas de tração do reforço. Adicionalmente, a distância crítica de deslocamento encontrada neste estudo é significativamente menor do que a recomendada pelas diretrizes da Administração Federal de Rodovias dos Estados Unidos (FHWA). Os resultados dos elementos finitos também demonstram que o uso de solo de enchimento de alta qualidade pode minimizar a interação entre os níveis inferior e superior. O uso de um comprimento uniforme de reforço de 0,6H para ambos os níveis reduz significativamente a deformação horizontal em comparação com a recomendação da FHWA de 0,6H e 0,35H para o nível inferior e superior, respectivamente.


**RESUMEN**
Los muros de suelo reforzado con geosintéticos (GRS) se han hecho cada vez más populares debido a sus numerosas ventajas. En algunos casos, estas estructuras se construyen en una configuración de varios niveles, lo que complica su comportamiento. Sin embargo, la respuesta de los muros de varios niveles no está suficientemente explicada en los manuales de diseño y estudios bibliográficos existentes. En este trabajo se investiga el comportamiento de los muros GRS con configuraciones de varios niveles mediante modelos numéricos de elementos finitos bidimensionales (2D). Este estudio compara el comportamiento de los muros GRS de dos niveles con los muros GRS simples (de un solo nivel). También examina el impacto de la distancia de desplazamiento, las propiedades de resistencia del relleno y los parámetros del refuerzo (espaciado...
vertical y longitud del refuerzo) en las deformaciones horizontales y las cargas de tracción del refuerzo en muros GRS de dos niveles. La adopción de una configuración de varios niveles para los muros GRS puede reducir significativamente tanto la deformación horizontal del muro como las cargas máximas de tracción del refuerzo. Además, la distancia de desplazamiento crítica encontrada en este estudio es significativamente menor que la recomendada por las directrices de la Administración Federal de Carreteras (FHWA). Los resultados de los elementos finitos también demuestran que el uso de suelo de relleno de alta calidad puede minimizar la interacción entre los niveles inferior y superior. El uso de una longitud de refuerzo uniforme de 0,6H para ambos niveles reduce significativamente la deformación horizontal en comparación con la recomendación de la FHWA de 0,6H y 0,35H para los niveles inferior y superior respectivamente.


1 INTRODUCTION

Retaining walls constructed using Geosynthetic Reinforced Soil (GRS Walls) are frequently employed for various geotechnical applications owing to their numerous advantages, such as the simple method of construction, ability to tolerate differential settlements, environmental compatibility, aesthetics, and excellent performance in both static and seismic loads. In addition, GRS Walls are less expensive than alternative walls, particularly in cases where the wall height is significant (Leshchinsky; Han, 2004). In many cases, GRS Walls are built in tiered arrangement instead of single walls for several reasons, including stability, significant wall heights, construction restrictions, and aesthetic aspects (Stuedlein et al., 2012; Yoo et al., 2011). However, compared to a single wall, the walls built in a multi-tiered arrangement are more complex since the upper and lower tiers interact and influence one another. These walls are considered one of the most complex structures as are back-to-back Mechanically Stabilized Earth (MSE) walls, and bridge abutments with MSE walls. As a result, in recent years, many researchers have been interested in studying the behavior of these structures. Among them, (Zheng; Fox, 2016; Ramalakshmi; Dodagoudar, 2018; Zheng et al., 2018; Doger; Hatami, 2020) for the stability analysis of bridge abutments with MSE walls and (Benmebarek; Djabri, 2017; Benmebarek; Djabri, 2018; Djabri; Benmebarek, 2016; Han, 2021) for studies on the behavior of back-to-back retaining walls.
GRS Walls with tiered configuration have been studied by many researchers using several methods such as numerical methods (Yoo et al., 2011; Yoo; Song, 2006; Yoo; Kim, 2008; Stuedlein et al., 2010; Liu, 2011; Mohamed et al., 2014; SeyediHosseininia; Ashjaee, 2018; Yoo, 2018; Nazari et al., 2022; Gao et al., 2022; Krishna Chaitanya; Karpurapu, 2023), limit equilibrium methods (Leshchinsky; Han, 2004; Wright, 2005; Osborne; Wright, 2004; Mohamed et al., 2013), and experimental methods (Stuedlein et al., 2012; Yoo et al., 2011; Yoo; Kim, 2008; Stuedlein et al., 2010; Liu et al., 2012; Yoo; Jung, 2004; Hung, 2008; Safaei, 2022; Yazdandoust; Taimouri, 2022). A parametric study of the multi-tiered wall was carried out by Leshchinsky and Han (2004) using two different analyses: continuum mechanics and limit equilibrium to investigate failure mechanisms and to determine tensile strength requirements based on parameters such as reinforcement length, stiffness, offset distance, etc. In their study, they found, among other things, that a greater offset distance can reduce the tensile strength requirements. Mohamed et al. (2014) performed FE analyses of centrifuge tests of GRS two-tier walls with different offset distances. According to their findings, the Federal Highway Administration (FHWA) guidelines are conservative in calculating reinforcement design strength and critical offset distance values. In a recent study, Yoo (2018) investigated the behavior of GRS walls with two tiers using the FE method. According to his investigation, the value of critical offset distance established by the FHWA guidelines is higher than what he found in his study.

Although the studies mentioned above yielded valuable insights into the understanding of the basic behavior of the multi-tiered GRS walls, further research is needed to improve current guidelines related to this type of walls.

In the current paper, the finite element (FE) method-based program PLAXIS 2D was performed not only to compare the performance of GRS walls with single-tier and multi-tiered configurations but also to analyze the effect of numerous factors on the behavior of this type of structure in static conditions. These parameters include the offset distance, backfill strength properties, and reinforcement parameters (vertical spacing and reinforcement length).
2 OVERVIEW OF DESIGN APPROACHES FOR GRS MULTITIER WALLS

For analyzing GRS multitier walls, current design methods NCMA (National Concrete Masonry Association, 2010) and FHWA (Elias et al., 2001; Berg et al., 2009) use empirical methods that are extensions of methods used in studying simple GRS walls (single-tiered). These methods depend on a key parameter known as the offset distance, D, representing the distance between tiers and has a significant impact on the performance and behavior of these structures.

In NCMA guidelines, the interaction between tiers is not taken into account in the case of the offset distance value (D) is greater than the lower tier's reinforcement length in the internal stability calculation or falls outside the failure zone for external analysis. In these guidelines, an equivalent surcharge replaces the upper tier, and its magnitude is calculated according to the offset distance value (Figure 1). The detailed description of this design procedure can be found in NCMA guidelines (National Concrete Masonry Association, 2010).

According to the FHWA design guidelines (Elias et al., 2001; Berg et al., 2009), GRS multitier walls are classified into three groups depending on the offset distance D (Figure 2). In the first case, in which the offset distance is small (D ≤ (H₁ + H₂)/20), with H₁ and H₂ representing the heights of the upper and lower tiers, respectively, the two tiers are treated as a simple wall, with a total height H equal to the sum of the upper and lower tier's height (H = H₁ + H₂). In the second instance, for intermediate values of offset distance (1/20(H₁ + H₂) < D ≤ H₂tan (90 - φᵣ)), where φᵣ represents the backfill's internal friction angle, the design involves treating
the upper and lower tiers as a compound wall. It’s worth noting that in this case, the recommended minimum lengths of reinforcement according to FHWA guidelines are $L_2=0.6H$ and $L_1=0.35H$ (i.e. $L_1=0.7H_1$) for the lower and the upper tier respectively. In the last instance, when $D > H_2 \tan (90 - \phi_r)$, the FHWA guidelines assume that there is no interaction occurs between the two tiers and recommend treating the upper and lower tiers as completely independent walls.

Figure 2. The classification of multitier GRS walls according to FHWA guidelines based on the offset distance $D$

Source: Berg et al., 2009

3 PARAMETRIC ANALYSIS

3.1 DESCRIPTION OF THE INVESTIGATED NUMERICAL MODEL

In the current work, two-dimensional (2D) FE studies were done to assess the impact of various parameters on two-tiered GRS walls’ performance. The study included the effect of offset distance, backfill strength properties (friction angle and cohesion), and reinforcement parameters (vertical spacing and length of reinforcement). The performance of GRS walls with two tiers was also evaluated in comparison to that of simple GRS walls (single-tiered). Additional information regarding the FE modeling will be presented and discussed in the upcoming sections.
3.1.1 Model configuration and modeling procedures

The investigated two-tiered GRS walls models were simulated using the FE Method incorporated in the 2D PLAXIS program. It should be noted that PLAXIS is a powerful software widely used in geotechnical engineering applications by numerous researchers (Benmebarek; Djabri, 2017; Benmebarek; Djabri, 2018; Djabri; Benmebarek, 2016; Mohamed et al., 2014; Yousfi et al., 2024). The reference model chosen in this study is basically a model that has been verified and used in previous studies (Yoo; Song, 2006; Yoo, 2018). Yoo and Song (2006) used this model and validated it by using the experimental data reported by Hatami and Bathurst (Hatami; Bathurst, 2005; Hatami; Bathurst, 2006) for the RMC wall (test wall at the Royal Military College). The numerical FE mesh and boundary conditions adopted for the reference model (two-tiered GRS wall case) are illustrated in Figure 3. The total wall height is $H = 10$ m, which consists of two tiers (Each tier is 5m high) with an offset of $2.5$ m ($D = 0.5H_2$) between tiers in the reference case. The models included a 10 m thick foundation soil layer, where the depth of the lower wall's embedment in the foundation soil was taken equal to 0.4 m. The wall facing was simulated using modular blocks with dimensions of 0.2 meters in height and 0.3 meters in length. For reference cases, whether single- or two-tiered GRS walls, the reinforcement's length was presumed to be 7 m ($L = 0.7H$), with a uniform vertical spacing of $e= 0.6$ meters. Noteworthy, the upper tier's reinforcement length for the reference cases is longer than the minimum value recommended by FHWA guidelines (i.e., $L_1 = 0.7H_1$), enabling a comparison of results between the two GRS wall configurations (single- and two-tiered). Furthermore, the reinforcement length will be further discussed in this parametric study.
The modeling of the soil and wall facing zones was performed under plane strain conditions using 15-noded triangular elements with 12 stress points. In the reference case (two-tiered wall with D = 0.5H2), the numerical model was composed of a total of 1,308 elements and 10,936 nodes. The only interface introduced in this model is that related to the interface between the soil and the wall's face, similar to many researchers, including Yoo (2018). For this purpose, a key interface parameter, Rinter (factor of the strength reduction), with a value of 0.7, was used to model the interface between the wall's face and the soil layer (Brinkgreve, 1998).

In order to minimize the boundary influence on system response, the lateral boundary in this study extends from the face of the lower tier to a distance of more than four times the upper tier's height (4H2) as shown in Figure 3. In terms of boundary conditions, as illustrated in Figure 3, the model's base is completely fixed, whereas the lateral boundaries are allowed to move vertically only while remaining fixed in the horizontal direction.

Regarding the modeling of the construction sequence, a layer-by-layer stage construction sequence was adopted. The first stage only included the foundation, then one block, a soil layer (each layer being 0.2 meters thick), and the reinforcement was added in each of the following stages.
3.1.2 Material models and properties

In current finite element analyses, two different soil zones were used (the backfill soil and the foundation). The two soils were simulated using a linear elastic-plastic model, which employs the Mohr-Coulomb failure criterion with the non-associated flow rule proposed by Davis (1968). The backfill soil used in the reference case was considered decomposed granite, which is classified as SP-SM by the USCS system, and its properties are chosen identically to Yoo (2018). The foundation soil is considered as a competent foundation and its properties are consistent with those reported by Damians et al. (2015).

The properties of the concrete modular blocks and the geogrid reinforcements are chosen also according to Yoo (2018). A linear model was used for the simulation of the concrete modular blocks assigning Young's modulus (E) as $10^6$ KPa and Poisson's ratio (ν) as 0.2. The layers of a geogrid reinforcement were modeled using a geogrid element integrated into PLAXIS 2D with tensile stiffness $E_A = 1000$ kN/m. Table 1 provides a summary of the material properties employed in this study.

<table>
<thead>
<tr>
<th>Parameters of soils</th>
<th>Backfill soil</th>
<th>Foundation soil</th>
<th>Modular blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight, $\gamma$ (kN/m³)</td>
<td>19</td>
<td>18.85</td>
<td>20</td>
</tr>
<tr>
<td>Elasticity modulus, $E$ (KPa)</td>
<td>$20 \times 10^3$</td>
<td>$110 \times 10^3$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Poisson ratio, $\nu$</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Internal friction angle, $\phi$ (°)</td>
<td>30</td>
<td>45</td>
<td>/</td>
</tr>
<tr>
<td>Cohesion, $C$ (KPa)</td>
<td>1</td>
<td>50</td>
<td>/</td>
</tr>
<tr>
<td>Dilatancy angle, $\psi$ (°)</td>
<td>10</td>
<td>15</td>
<td>/</td>
</tr>
</tbody>
</table>

Source: Authors

3.2 RESULTS AND DISCUSSION

3.2.1 Influences of the offset distance

In this investigation, the criteria selected for evaluating the influence of offset distance on the two-tiered GRS walls behavior were the lateral wall displacement and the maximum tensile loads in the reinforcement.
3.2.1.1 Horizontal wall deformation

Figure 4 compares the horizontal displacements for GRS walls with single-tier and multi-tiered configurations with different offset values. As illustrated in Figure 4, the lateral displacements in the case of GRS walls with multi-tiered configurations were smaller compared to those of the simple GRS wall (single-tiered) depending on the offset distance values. As can also be seen, as the offset distance values increase, the wall’s lateral displacement decreases. Thus, by adding an offset to the wall the deformation can be reduced. As an example, the maximum lateral displacement in the case of two-tiered GRS walls that had a 6.0 m offset \((D=1.2H)\) was only 33% of the displacement observed in the case of a simple GRS wall. Moreover, when the offset distance values are small, significant wall displacement develops at the lowest portion of the upper tier (at the junction of two tiers).

It is important to note that beyond an offset distance of 1.2H, no significant reduction in wall deformation is observed. This suggests that when the tiers are offset by more than 1.2 times the height of the lower tier \((D > 1.2H)\), their interaction becomes negligible.

Figure 4. Comparison of horizontal wall deformation for different offset distance

3.2.1.2 Reinforcement tensile load

The variation of maximum tensile loads for various values of offset distance is shown in Figure 5. As in the case of horizontal displacements of wall facings,
the maximum tensile loads reduce with the increasing offset distance. For instance, in the case of two-tiered GRS walls with a 6.0 m offset (D=1.2H2), the maximum values of tensile loads across all reinforcement layers are approximately 60% smaller compared to those in the case of a simple GRS wall.

Similar to the case of the horizontal wall deformation, no significant decrease in maximum reinforcement tensile load is observed when D > 1.2H2. Hence, the two tiers don't significantly influence each other when they are offset by a value greater than 1.2 times the lower tier's height (D > 1.2H2). In addition, it is worth noting that for the lower tier, maximum tensile loads change significantly with D, whereas minimal changes occur in the upper tier.

![Figure 5 Effect of offset Distance on maximum reinforcement tensile load](image)

**3.2.2 Effect of backfill soil properties on critical offset distance**

In this section, a number of analyses were carried out considering various backfill strength properties (friction angle and cohesion) to examine the backfill soil quality's influences on critical offset distance (defined as the distance between two tiers at which they can operate independently).

**3.2.2.1 Effect of the cohesion**

The effects of backfill cohesion were investigated by using three values of cohesion (1Kpa, 5KPa, and 10KPa). In Figure 6, the impact of backfill cohesion on
the maximum lateral wall displacement is illustrated for both the upper and lower tiers with different offset distances. As shown, the critical offset distance value tends to decrease when the backfill has a higher cohesion is used.

Figure 6. The influence of backfill cohesion on critical offset distance for (a) Lower Tier and (b) Upper Tier

The result of the variation of maximum tensile loads for various values of backfill cohesion for upper and lower tiers for different offset distances is presented in Figure 7. In the same way as the case of the horizontal wall deformation, the results show that the critical offset distance’s value decreases when the backfill cohesion increases. Therefore, it can be said that the use of granular soil with some cohesion can effectively lessen the extent to which the upper and lower tiers of a two-tiered GRS wall mutually influence, which means reducing the critical offset distance value.

Figure 7 the influence of backfill cohesion on critical offset distance for (a) Lower Tier and (b) Upper Tier

Source: Authors
3.2.2.2 Effect of the friction angle

To investigate the effect of backfill friction angle on critical offset distance, three values of friction angle were chosen (30°, 40°, and 50°). Figure 8 shows the changes in the maximum normalized horizontal wall displacement of the upper and lower tiers based on the backfill friction angle. According to Figure 8, an increase in the backfill friction angle results in a decrease in the critical offset distance value. The results show that the critical offset distance is approximately 1.2, 0.8, and 0.6 for a friction angle equal to 30°, 40°, and 50°, respectively.

![Figure 8. The influence of backfill cohesion on critical offset distance for (a) Lower Tier and (b) Upper Tier](image)

Source: Authors

The change of maximum tensile loads for various values of backfill friction angle in each tier of the GRS wall with different offset distances is presented in Figure 9. Again, the results demonstrate that the value of the critical distance decreases when the backfill friction angle increases, as seen in the case of horizontal wall deformation.

![Figure 9. The influence of backfill friction angle on critical offset distance for (a) Lower Tier and (b) Upper Tier](image)

Source: Authors
Table 2 presents a comparison between critical offset distance values obtained in this finite element study and those established by the FHWA design guidelines for various backfill friction angles. According to the results of horizontal wall displacement and the maximum tensile loads in reinforcement layers, the value of critical offset distance in each case of the backfill friction angle studied is approximately 30% less than what was calculated using the FHWA guidelines method.

<table>
<thead>
<tr>
<th>friction angle, $\varphi$ (°)</th>
<th>Critical offset distance, $D_{cr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHWA (Experimental)</td>
</tr>
<tr>
<td>30</td>
<td>1.73</td>
</tr>
<tr>
<td>40</td>
<td>1.19</td>
</tr>
<tr>
<td>50</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Source: Authors

3.2.3 Effects of reinforcement parameters

To identify and compare the influence of reinforcement parameters on both walls (single- and two-tiered GRS walls), numerous numerical models have been conducted. These models aim to assess the influence of vertical spacing and reinforcement length on horizontal wall deformation.

3.2.3.1 Effects of vertical spacing

In this part, the impact of vertical reinforcement spacing on lateral displacement was investigated for both single- and two-tiered GRS wall configurations. Four distinct reinforcement spacings (0.2, 0.4, 0.6, and 0.8 m) were considered, as illustrated in Figure 10. Evidently, the closer spacing of the reinforcements led to a reduction in lateral displacement for both single-tiered and two-tiered configurations. Furthermore, it is evident that in every case, the lateral wall displacement was decreased by using a multi-tiered configuration compared to single-tiered walls, which once again confirms their good performance in reducing lateral displacements. The obtained results also indicate that the decrease in lateral displacement becomes somewhat more significant with increased spacing. For instance, when the spacing is 0.2 m, the lateral displacement of the single-tiered
wall is 21% greater than that of the two-tiered GRS walls, while this difference increases to 28% greater for the single-tiered wall with 0.8 m spacing.

Figure 10. Effects of vertical spacing on horizontal wall deformation for single-tier (SW) and multi-tiered (TW) case

3.2.3.2 Effects of reinforcement length

In Figure 11, the reinforcement length impact on lateral wall displacement is compared between the two configurations (single and tiered walls). It was shown that an augmentation in the length of reinforcement results in a reduction of lateral wall displacements for both single and two-tiered wall configurations. In addition, this reduction in displacement becomes less significant when the reinforcement length reaches or exceeds 0.6H, suggesting a diminishing return in deformation improvement with further lengthening of reinforcement. It is also worth noting that this value of 0.6H is consistent with the requirement specified in the FHWA design guidelines for the case of single-tiered walls. However, it exceeds the corresponding requirement for two-tiered walls, where the recommended length is 0.6H for the lower wall and 0.7H₁ (0.35H) for the upper wall, as mentioned earlier. Therefore, to further evaluate and better understand the influence of reinforcement length on the two-tiered GRS wall behavior, particularly concerning lateral wall displacement, a subsequent study was conducted. For this purpose, the impact of reinforcement length on wall displacements was examined in both the upper (L₁) and lower (L₂) tiers.
Figure 11. Comparison of horizontal wall deformation for different reinforcement lengths

Figure 12 illustrates the changes in the maximum lateral wall displacement of the lower tier with reinforcement lengths $L_1$ and $L_2$, while Figure 13 shows their influence on the upper tier.

Figure 12. Changes in the maximum lateral wall displacement of the Lower Tier according to reinforcement lengths $L_1$ and $L_2$

Similar to what was seen in the comparison between the simple and tiered walls, the lateral wall displacement decreases as the length of the lower or the upper reinforcement increases, up to a value of $0.6H$, where the decrease becomes slight (for both lengths $L_1$ and $L_2$). Therefore, these results confirm, once again, that adopting a minimum reinforcement length of $L_1 = L_2 = 0.6H$ for the two
tiers (upper and lower) is recommended. Also, these results align with those reported by Gao et al. (2022), who conducted parametric studies using the finite difference method.

Figure 13. Changes in the maximum lateral wall displacement of the Upper Tier according to reinforcement lengths $L_1$ and $L_2$

4 CONCLUSIONS

In this paper, geosynthetic reinforced soil (GRS) walls with two-tiered configurations were investigated using a finite element method, aiming to better understand their static performance and to compare their behavior with single-tiered walls under the same conditions. This research provides valuable practical insights for engineering applications and contributes to the academic knowledge base on these structures. In light of the findings of this study, the key conclusions are outlined as follows:

- compared to a wall with a single tier, a wall in multi-tiered configuration with the same conditions can significantly reduce not only the lateral displacement but also reinforcement loads;
- for the multi-tiered walls, both the lateral wall displacements and the reinforcement load decrease as the offset distance increases in the two tiers (upper and lower);
• considering the criteria of the horizontal wall deformation and maximum tensile loads in reinforcement, the results presented in this numerical investigation suggest that the critical offset distance for different backfill friction angles is significantly lower than those recommended by FHWA guidelines, which is consistent with previous studies;

• in the case where the offset distance value is small, the significant horizontal displacements and reinforcement loads occurred approximately at the bottom zone of the upper wall, specifically at the connection zone between the two tiers;

• the critical offset distance value decreases when the backfill friction angle increases, so it is possible to reduce the interaction between the two tiers by using soils with high friction angle;

• using soils containing cohesion for GRS walls with tiered configurations reduced the value of the critical offset distance, leading to a reduction in both maximum wall displacements and reinforcement loads in both tiers. It suggests that the utilization of granular soil with some cohesion in the construction of multi-tiered walls leads to a reduction in the level of the mutual interaction between the two tiers for a specified offset distance;

• for multi-tiered walls, the current study demonstrates that using a uniform reinforcement length of 0.6H for both tiers significantly reduces horizontal deformation compared to the FHWA recommendation of 0.6H and 0.35H for the lower and the upper tier respectively.

Despite providing significant results on the performance of GRS walls with two-tiered configurations, this study has several limitations that need to be addressed. First, the analysis was restricted to walls with only two tiers, which may not fully capture the complexities and behaviors of multi-tiered walls with three or more tiers. Additionally, the study did not consider the effects of other factors, such as the type of foundation soil and the type of reinforcement, which can significantly influence the stability and performance of GRS walls. Furthermore, the research was limited to static loading conditions and did not explore the impacts of dynamic loading, such as seismic loads. Hence, further investigation is necessary to fully address these parameters in future work, with the intention of further enriching the understanding of the behavior of these structures.
REFERENCES


