Static Performance of Geosynthetic Reinforced Soil Walls with Peripheral Soil–Cement Mixtures

Mehdi Derakhshandi¹,*, Ghazale Rahmati² and Mani Sadjadi¹

¹Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.
²Department of Civil Engineering, Arak University, Arak, Iran.

Abstract. Recently, much effort has been devoted to improving the performance of geosynthetic reinforced walls under various stress conditions. In this research, the effect of using cemented mixed soil as a backfill material is studied on the static response of geosynthetic reinforced soil (GRS) walls. For this, numerical models based on a finite-difference code are made according to one of the Royal Military College’s (RMC) full scale test walls with a segmental facing. Different arrangements of soil reinforcement are considered in the presence of cemented sandy soil and sandy soil alone. In the cement-treated approach, each reinforcement layer is surrounded by a 30 cm cemented sand soil. The results show that using cement-treated sandy soil decreases the maximum deformation of the wall by as much as 75% compared with the case where untreated sandy soil is used. Moreover, by using cemented soil around reinforcements, the reinforcement forces reduce considerably. Therefore, increasing the number of reinforcement layers in the backfill will decrease the face wall deformation as well as the reinforcement forces, which are not cost-effective in many situations. It is also suggested that using the cement-treated technique can be an efficient cost-saving method compared with common GRS walls.

Keywords: Geogrid; Reinforced retaining walls; Cement-treated soil; Numerical model; Parametric analysis

1. Introduction

In order to improve the performance of earth structures, various techniques have been proposed up to now. In 1963, stabilizing the soil retaining walls entered a new era by using galvanized steel strips as reinforcement. By introducing geosynthetic reinforcements in the 1980s, GRS walls gained popularity due to several advantages, such as cost-effectiveness, and the ability to tolerate deformation and settlement compared with the other type of soil retaining walls [1-3]. Moreover, since the soil retaining walls are considered as permanent structures, the safety and serviceability during their lifetime should both be taken into account in their design. For this purpose, there are many recommendations in guidelines and provisions for evaluating the maximum horizontal deformation of reinforced soil retaining walls [4-6].

The main causes of deformation in GRS retaining walls in the absence of surcharge loading are deformation of reinforced soil section and backfill soil, post-construction deformation,
deformation due to construction defects, and deformation due to compaction and yielding of the foundation. Therefore, several studies have been carried out to assess the effects of these factors on the behavior of GRS retaining walls [7].

Time-dependent properties of reinforced soils (i.e., backfill soil creep and time-dependent properties of geosynthetic reinforcements) are important causes of post-construction deformation in GRS retaining walls that cannot be neglected in analyses (e.g., [1, 8-11]). In this regard, Liu 2012 employed calibrated finite element models to study the short-term (end of construction (EOC)) and long-term (10 years of creep) performance of GRS retaining walls [12]. They investigated the effects of reinforcement spacing, type of backfill soil, reinforcement stiffness and length. The results showed that deformation of a reinforced soil block was considerably affected by spacing and stiffness of reinforcement layers. They observed that the reinforcement length had a negligible effect on the deformation of a reinforced soil block. In addition, it was observed that lengthening the reinforcement layers led to a significant decrease in lateral displacement of the back of the reinforced soil section [11].

Other studies on the backfill material indicated that the type of soil had an important effect on the stiffness of the reinforced soil zone and consequently the active earth pressure at the back of the reinforced soil [7, 13-15]. In general, it is accepted that the strength of soil or active earth pressure coefficient is more important than the soil stiffness (e.g., [7, 16]). However, using reinforcements with high stiffness in a dense spacing arrangement reduces the effect of soil strength on deformation of the reinforced soil zone and, thus, soil stiffness and strength should be considered simultaneously for assessment of lateral displacement of GRS walls [17].

Recently, cement-treated soils have been developed to improve serviceability of various GRS structures. For instance, the GRS bridge abutment with cement-treated backfill is now one of the standard soil structures for high-speed train lines. In order to evaluate the long-term performance of this type of GRS structure, especially against severe seismic loads, many investigations have been conducted based on the physical model in the laboratory and full-scale model in the field [18-24]. The results of these studies, in which cement-treated soils were used as a backfill immediately behind the GRS bridge abutment, showed that the lateral stiffness of the structure increases, resulting in a decrease in deformation of the walls subjected to severe lateral loading. Moreover, greater integrity has been observed between backfill and abutment. In addition to improving the performance of GRS walls, using cement-treated soil can result in a decrease in thickness of the wall without a need to use pile foundations, which is more cost-effective than common GRS walls [25].

As mentioned before, many studies have been performed on the behavior of GRS walls under operational stress conditions to optimize the performance and to minimize the costs. Using cement-treated reinforced soil can be an effective alternative to meet these goals. However, there is no economic justification to implement this method for all projects due to the massive volume of cement required. Therefore, the objective of this study is to propose a simple method to improve the performance of GRS walls by applying a limited amount of cement adjacent to the reinforcement layers. For this purpose, the finite-difference analysis is employed to investigate the efficiency and the cost-effectiveness of this technique compared with common GRS walls with different reinforcement arrangements. According to previous studies on the behavior of cement-treated soil, it seems that using cement-treated soil in reinforcement layers can improve the performance of GRS walls.
In this research, a numerical analysis is conducted on a large-scale GRS wall up to the end of construction. The numerical model is verified with the large-scale test constructed under the plane strain condition [26]. The results include the horizontal displacement of facing and the reinforcement forces are compared with those attributed to the same wall but with cement-treated sandy soil around the reinforcements.

2. Numerical Approach

In this study, the finite-difference code, Fast Lagrangian Analysis of Continua (FLAC) [27], is employed to investigate the plane-strain behavior of the GRS retaining walls. The numerical model is calibrated using the data presented from Royal Military College (RMC) physical models developed by Hatami and Bathurst (2005) [26]. Bathurst et. al. (2001) [28] conducted three instrumented, large-scale tests to explore the performance of GRS segmental walls under working stress. In the following section, the physical model test is described briefly.

2.1 The RMC Physical Model Test Description

A 3.6 m high modular block (segmental) GRS retaining wall with a target-facing batter of 8° from the vertical is constructed on a rigid foundation. The wall with six polypropylene (PP) geogrid reinforcement layers is constructed according to the AASHTO standard requirements. Accordingly, the spacing between reinforcement layers is 0.6 m and the ratio of the length of reinforcement to the height of the wall (L/H) is 0.7. Moreover, using mechanical connections, the reinforcement layers are rigidly attached to the facing (see Figure 1).

![Figure 1. Cross-section of segmental reinforced soil retaining wall (RMC) physical models utilized for calibration of numerical model [26]](image)

A discrete column of solid concrete blocks is employed as the wall facing. Each concrete unit is 20 kg (300 mm width, 150 mm height and 200 mm length). The poorly graded sand soil (Unified Soil Classification – SP) is used as backfill with $D_{50} = 0.34$ mm, coefficient of curvature $Cc = 2.25$, and coefficient of uniformity $Cu = 1.09$.

2.2 Finite-Difference Procedure and Model

The FLAC 2D program [27] is used to simulate the plane-strain behavior of the GRS model test. The numerical procedure includes the modeling of backfill, facing modular blocks and reinforcement layers, in addition to specifying the characteristics of interfaces and boundaries. It should be noted that the stage-construction procedure is considered in the simulation for placing each soil layer, course of blocks and geogrid reinforcement layer.

2.3 Modeling of Backfill Soil

The continuum zone is utilized to simulate the backfill soil as a homogeneous, isotropic, nonlinear elasto–plastic material with Mohr–Coulomb failure criterion and dilation angle. Using the stress-dependent hyperbolic constitutive model [29], a nonlinear elastic behavior is considered for the backfill. This constitutive model is implemented using the FISH language. In this hyperbolic model, the tangent elastic modulus, $E(t)$, the bulk modulus, $B$, and the tangent Poisson’s ratio, $\nu(t)$, of soil are calculated as:
\[ E(t) = \left[ 1 - \frac{R_f \times (\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)_f} \right]^2 K_e \times \frac{P_a (\sigma_3 / P_a)^n}{K_e \times P_a (\sigma_3 / P_a)^m} \]  

(1)

\[ B = K_b \times P_a (\sigma_3 / P_a)^m \]  

(2)

\[ \nu(t) = 0.5 - \frac{E_t}{6B} \quad , \quad 0 < \nu_t < 0.49 \]  

(3)

Where \( K_e \) is the elastic modulus number; \( (\sigma_1 - \sigma_3)_f \) is the deviatoric stress at failure; \( R_f \) is the failure ratio; \( \sigma_1 \) and \( \sigma_3 \) are major and minor principal stresses, respectively; \( n \) is the elastic modulus exponent; \( K_b \) and \( m \) are the bulk modulus number and bulk modulus exponent, respectively; and \( P_a \) is atmospheric pressure. The properties of the backfill material are listed in Table 1:

**Table 1.** Backfill soil properties [26]

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<thead>
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<th>Property</th>
<th>Value</th>
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<tr>
<td>E</td>
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<td>B</td>
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<td>( \nu(t) )</td>
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It should be noted that the boundary of backfill is extended to five times the wall height to minimize the possible effect of the far-field boundary on simulation response [30]. In addition, a parametric study is conducted to study the effect of using cement-treated soil adjacent to geogrid layers on the behavior of the wall. The mechanical properties of cemented poorly graded sand soil are chosen for their similarity to the results of triaxial tests in the literature [31, 32]. The cement content of the soil is considered to be 5%. The mechanical properties of cement-treated soil are given in Table 2.

**Table 2.** The properties of cement-treated soil [32]

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<td>E</td>
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<td>( \nu(t) )</td>
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where \( E \) is Yong modulus of cemented soil with 15 cm thickness on either side of reinforcement layers, which is defined by FLAC FISH programming as a hyperbolic formulation. The analysis in this part has been conducted for backfill sandy soil and backfill cemented sandy soil in different reinforcement layers.

### 2.4 Modeling of Reinforcement Layers

Reinforcement layers are modeled using a cable element with strain-dependent tangent tensile stiffness \( J_t(\varepsilon) \), tensile strength \( T_y \) and no compressive strength. Cable elements are one-dimensional axial elements with elasto–plastic behavior. The soil–reinforcement interaction can be simulated by using the FLAC grout utility with zero thickness, zero cohesion and interface friction angle of 0.75\( \phi \) (\( \delta_{gr} \)). However, previous studies show that no slippage may occur between the reinforcement elements and the backfill soil under working stress conditions [17, 26, 33]. Therefore, in this study, the reinforcement structural nodes are rigidly connected to the backfill grid points. The reinforcement material properties used in numerical simulations are summarized in Table 3. Moreover, the reinforcement layers are attached rigidly to the facing based on the use of mechanical connections in the model.

**Table 3.** The reinforcement material properties [26]

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<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>E</td>
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<td>B</td>
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<td>( \nu(t) )</td>
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### 2.5 Modeling of Facing System

The linear elastic continuum zones are used to model the facing wall. The nulled zones with zero thickness that include interfaces are used to divide the facing column of walls into 24
rows of concrete modular blocks. The stiffness of the facing column is determined by the
values of interface shear stiffness between modular blocks obtained from the results of direct
shear tests conducted in the laboratory.

2.6 Interfaces and Boundary Conditions

The interface elements between different contact surfaces and joints are simulated by linear
spring–slider systems. The interface shear strength is defined by the Mohr–Coulomb failure
criterion in which the shear and normal interface stiffness (\(K_s\) and \(K_n\), respectively) values
must be defined to control the relative interface movement. Therefore, the values of interface
stiffness should be selected to match physical test results. In the numerical simulations, the
boundary conditions have been defined to represent the RMC model test facilities accurately.
In this regard, a fixed boundary condition is applied at numerical grid points in the X
direction on the backfill far-end boundary to match the bulkheads that are used at the back of
the test facility. In addition, in order to simulate the concrete foundation of the RMC model
test, a fixed base condition is assumed in both \(X\) and \(Y\) directions on the bottom of the model
[26]. The interface parameters used in the current study are reported in Table 4.

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<th>Table 4. Interface properties [26]</th>
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| Moreover, in order to consider the compaction effects in the simulations, a uniform vertical
| stress of 8 kPa has been applied at each construction stage to the entire surface. Since the wall
| was constructed by using the bottom-up approach, this vertical stress increment was removed
| after solving the model to equilibrium at each stage. Static analyses are conducted for
| identical segmental walls with different reinforcement layer arrangements. Walls are modeled
| with six, five, four and three reinforcement layers at 60 cm, 75 cm, 90 cm and 120 cm
| vertical distances, respectively. The schematic cross-section of the finite-difference model is
| shown in Figure 2. |

**Figure 2.** The finite-difference model of GRS wall with six layers at 60 cm vertical distance

2.7 Validation of Finite-Difference Procedure

Any numerical simulation needs to be validated before the results are analyzed. In the current
investigation, a numerical model made by FLAC is verified against the data gathered from
the RMC laboratory’s physical model. More details of the physical model can be found in the
study of Hatami and Bathurst 2005 [26]. The predicted horizontal displacement and
connection loads of the GRS walls with six reinforcement layers at 60 cm vertical distance
are compared with measured identical test data. As shown in Figure 3, the results of the
numerical model are in a satisfactory agreement with the laboratory results.

It should be noted, the reported displacement value at each level in the Figure 3(a) represents
the magnitude of the lateral displacement of the corresponding facing block from the time of
potentiometer placement to the end of construction. Hence, these plots should not be confused
with the actual wall deformation profiles at the end of construction. Moreover, Figure 3(b)
shows satisfactory agreement between the calculated and measured connection loads with the
exception of Reinforcement Layers 1 and 2. The same trend has been seen in Hatami and
Bathurst (2005) numerical study using FLAC software in comparison with results of the same
full-scale test wall. They explained that these discrepancies might result from the local over-
compaction of soil directly behind the facing units at the bottom of the walls.
3. Results and Discussion

In the following sections, a comparison will be made between the results of static analyses of segmental GRS walls with different reinforcement layer arrangements in the presence and the absence of cement-treated reinforced soil. The schemes of reinforcement distribution include six, five, four and three reinforcement layers at 60 cm, 75 cm, 90 cm and 120 cm vertical distances, respectively. In addition, in all numerical simulations, the thickness of cement-treated soil is considered to be 15 cm at each side of the reinforcement layer.

3.1 The Horizontal Deformation

In this part, the horizontal deformation of GRS wall facings with different backfill conditions is presented. It should be noted that, since the wall foundation is modeled as rigid and the effect of compaction efforts on wall deformation is considered at different stages of construction, the lateral displacement of the wall is mainly due to deformation in the reinforced zone as well as the unreinforced soil zone behind the facing. The reinforcement stiffness factor $A = \frac{J}{K_a \gamma S_v}$ can be introduced as one of the most efficient material parameters affecting the lateral deformation of GRS walls, where $J$ is the reinforcement stiffness; $K_a$ is the Rankin active earth pressure coefficient; $\gamma$ is the unit weight of the soil; $H$ is the wall height; and $S_v$ is the vertical spacing between layers of reinforcement [7]. For instance, as can be observed in Figure 4(a) and (b), an increase in the number of reinforcements (i.e., increase in $A$) causes a decrease in horizontal deformation of the wall for different backfill conditions. These observations confirm the efficient role of $A$ in controlling the wall deformation.

In Figure 5, the lateral displacement of GRS walls is compared for cement-treated backfill relative to the untreated backfill using the same scheme of reinforcement distribution. This Figure clearly indicates that using cement-treated soil adjacent to the reinforcements significantly decreases the deformation of the facing. The maximum amounts of decrease in wall deformation along the height of the facing are presented in Table 5.

<table>
<thead>
<tr>
<th>Table 5. The maximum percentage reductions in wall facing deformation using cement-treated backfill compared with untreated backfill</th>
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As a result, using cement-treated backfill can be attributed to greater stiffness of the reinforced soil in reinforced soil zone especially in areas adjacent to the reinforcement layers. Therefore, due to strain compatibility between the reinforcement and the soil, the potential slippage at the reinforcement–soil interface becomes smaller, which decreases the reinforced soil zone deformation. Furthermore, the horizontal movement of the unreinforced soil zone behind the reinforced soil block has a considerable effect on the wall facing deformation. The amount to which this source contributes to wall face displacement depends on the level at which the zero force line intercepts the back of the reinforced soil block. The zero force line is a theoretical line beyond which the soil does not make a significant contribution to wall face deflection. As can be observed in Figure 6, the internal friction angle of backfill soil determines the slope of the zero force line. Thus, the internal friction angle of backfill soil is the other important parameter that affects the deformation of GRS walls [7].

Figure 3. The validation of finite difference procedure with RMC physical model a) relative facing displacement b) connection load
Using cement-treated soil adjacent to reinforcement layers increases the inertial friction angle of backfill soil. This makes the area of unreinforced retained fill above the zero force line smaller. Hence, it appears that the movement of unreinforced soil behind the reinforced soil block becomes smaller, which leads to a decrease in wall deformation. Moreover, as can be seen in Figure 5, applying cement-treated soil causes the locus of maximum deformation of the wall to move down from $H/2$ to $H/3$. This is also due to the reduction of the unreinforced soil zone behind the reinforced soil zone, which contributes to the top wall deformation.

Table 6 presents the maximum reduction in facing displacement in the presence of the reinforcement layers. The numerical results suggest that using cement-treated soil results in the maximum amount of reduction in deformation, about twice as much as untreated soil with an increased number of reinforcement layers. This means that applying cement-treated soil increases the effect of using the reinforcement layers on the reduction of horizontal deformation of the wall. It can also be observed that under both backfill soil conditions the optimal number of reinforcement layers is four. Increasing the number of reinforcement layers beyond four does not seem to cause a significant reduction in wall deformation.

The lateral deformation of wall facing under static conditions is shown in Figure 7 for different schemes of reinforcement distribution using cement-treated backfill, compared with untreated backfill using six layers of reinforcement. As can be observed in this Figure, in the presence of cement-treated soil the deformation of the wall with the minimum number of reinforcement layers (i.e., three layers) becomes smaller compared with deformation in the wall without cement-treated soil with the maximum number of reinforcement layers (i.e., six layers). This important finding implies that the use of the recommended method in this study can decrease the number of reinforcement layers, which may be a cost-effective technique in the construction of GRS walls.

In this section, the maximum force in the reinforcement layers along the height of the wall is compared for different backfill conditions. As illustrated in Figure 8, using the cement-treated soil adjacent to the reinforcement layers causes a considerable reduction in the maximum reinforcement forces.

It should be noted that the magnitude of reinforcement forces in GRS walls depends on the shear strength mobilized in the backfill soil [7]. Applying cement-treated soil increases the
soil-reinforcement contact efficiencies, which enhances both the shear strength of the backfill soil and the pullout resistance along the soil-reinforcement interface [34]. Therefore, a smaller force would be required in the GRS wall system to maintain equilibrium. This results in a reduction in the reinforcement maximum forces. Table 7 shows the maximum percentage reduction of reinforcement forces for different schemes of reinforcement distributions.

Table 7. Comparison of the maximum percentage reduction of reinforcement force due to using cement-treated soil

Figure 9 shows distribution of forces along reinforcement layers for cement-treated and untreated backfill soil reinforced with five geogrids. It can be observed that in the presence of cemented soil a considerable force reduction occurs along the reinforcement layers compared with untreated reinforced soil.

Figure 9. The variation of force distribution along 5 reinforcement layers (a) untreated backfill soil, (b) cement-treated backfill soil

Figure 10 (a) and (b) demonstrate the effect of increasing the amount of reinforcement on the maximum forces of reinforcement layers. As can be observed in these figures, for both reinforced soil conditions, as the number of reinforcement layers is increased, the largest magnitude of reinforcement forces is reduced. This is due to an increase in $\Lambda$, which leads to a decrease in reinforcement forces. According to numerical modeling results, the second reinforcement layer experiences a higher maximum force compared with the other reinforcement layers in all the cases studied.

Figure 10. Comparison the maximum magnitude of reinforcement forces with increasing the number of reinforcement layers using (a) untreated backfill soil (b) cement-treated backfill soil

The maximum forces in the reinforcement layers under operational conditions are shown in Figure 11 for different schemes of reinforcement distribution using cement-treated backfill against untreated backfill using six layers of reinforcement. It is clear in this figure that in the presence of cement-treated soil the maximum reinforcement forces along the height of the wall, even with the minimum number of reinforcement layers (i.e., three layers), is smaller than the untreated reinforced soil with the maximum number of reinforcement layers (i.e., six layers). These observations are in agreement with our previous suggestion that using cement-treated soil adjacent to the reinforcement is a cost-effective technique in the construction of GRS walls.

Figure 11. Comparison of the maximum reinforcement force in the presence and in the absence of cement-treated backfill

In summary, according to the results have been achieved in this study, using the peripheral soil cement mixture can be a trustworthy method to improve the performance of GRS walls. It should be mention that this improvement technique can be more economical than typical types of GRS walls with rectangular or trapezoidal soil cemented zone due to reduction of cement consumption. Although for special cases, more investigation and comparison recommend between these methods.

4. Conclusion

Geosynthetic reinforced soil (GRS) retaining walls are widely used in many countries as permanent structures. However, safety of these walls is always the first concern in their
design. In order to improve the behavior of this kind of soil structure, various improvement methods have been recommended, such as using cement-treated reinforced soil. In this paper, a numerical simulation has been conducted to study the effectiveness of using cement-treated soil with limited thickness (30 cm) adjacent to reinforcement layers. The most important findings of this study are summarized below:

1. Increasing the number of reinforcement layers, in the presence and in the absence of cement-treated reinforced soil, results in a decrease in wall deformation by increasing the reinforcement stiffness factor ($\psi$).
2. Using cement-treated soil adjacent to reinforcement layers reduces the wall facing deformation considerably (e.g., up to 75% for a wall including six layers of reinforcement).

This reduction is a result of decreasing deformation in the reinforced zone and displacement in the unreinforced soil block behind the reinforced zone.
3. Adding cement to backfill soil around the reinforcement layers changes the deformation mode of facing blocks. The maximum horizontal deformation due to reduction of unreinforced soil behind the reinforced zone and beyond the zero force line is lowered from $H/2$ to $H/3$.
4. Applying cemented soil has a significant effect on reduction of the maximum reinforcement forces. This is caused by increasing the shear strength of backfill soil around the reinforcement layers.
5. In the presence of 30 cm cement-treated soil adjacent to the reinforcement layers, the performance of GRS walls is considerably improved. This finding implies that using this technique can be a cost-saving construction alternative where a large number of reinforcement layers is required.

References


**Biographies**

**Mehdi Derakhshandi** received his BS in Civil Engineering from Isfahan University of Technology in 1998 and his MSc degree in Soil mechanics and Foundation Engineering in 2000. He earned his PhD degree from Amirkabir University of Technology in 2006. He is currently an Assistant Professor of Science and Research Brunch, Islamic Azad University of Tehran. His research activities include cyclic behavior of soil materials by physical modelling and element testing.

**Ghazale Rahmati** earned his BS in Civil Engineering and his MSc in Geotechnical Engineering from Arak University. The study of static and seismic performance of the geosynthetic reinforced soil systems is her research interests. She is currently a Geotechnical Engineer.

**Mani Sadjadi** is currently a PhD candidate in Geotechnical Engineering at Research Brunch of Islamic Azad University, Tehran, Iran. His PhD thesis is on the performance of rocking soil-structure systems on improved soils. His research interests include geotechnical earthquake engineering, soil-structure interaction, and soil improvement.
List of figure captions

**Figure 1.** Cross-section of segmental reinforced soil retaining wall (RMC) physical models utilized for calibration of numerical model [26]

**Figure 2.** The finite-difference model of GRS wall with six layers at 60 cm vertical distance

**Figure 3.** The validation of finite difference procedure with RMC physical model a) relative facing displacement b) connection load

**Figure 4.** Horizontal deformation of GRS wall (a) using untreated backfill soil (b) using cement-treated backfill soil

**Figure 5.** Comparison of horizontal deformation of GRS wall under static condition in the presence and absence of cement-treated backfill (a) 3 reinforcement layers (b) 4 reinforcement layers (c) 5 reinforcement layers (d) 6 reinforcement layers

**Figure 6.** Schematic GRS wall geometry and zero force line [7]

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**Figure 8.** The maximum reinforcement force in the presence and the absence of cement-treated soil (a) 3 layers (b) 4 layers (c) 5 layers (d) 6 layers

**Figure 9.** The variation of force distribution along 5 reinforcement layers (a) untreated backfill soil, (b) cement-treated backfill soil

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List of table captions

Table 1. Backfill soil properties [26]

Table 2. The properties of cement-treated soil [32]

Table 3. The reinforcement material properties [26]

Table 4. Interface properties [26]

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<thead>
<tr>
<th>Cable No.</th>
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<tr>
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<td>2.792E+02</td>
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<td>5.297E+02</td>
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<td>5</td>
<td>5.605E+01</td>
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<td>Unit weight</td>
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* unloading-reloading modulus number assumed to be 1.2×$K_e$ for compacted sand [29]
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<table>
<thead>
<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>$E$, Young’s modulus (MPa)</td>
<td>200</td>
</tr>
<tr>
<td>$C$, Cohesion (kPa)</td>
<td>200</td>
</tr>
<tr>
<td>$\Phi$, Internal friction angle (˚)</td>
<td>46</td>
</tr>
<tr>
<td>$\nu$, Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------</td>
</tr>
<tr>
<td>$\delta_{sr}$</td>
<td>33</td>
</tr>
<tr>
<td>$T_y$ (kN/m)</td>
<td>13</td>
</tr>
<tr>
<td>$J_e$ (kN/m)</td>
<td>(119-2938) $\varepsilon$</td>
</tr>
<tr>
<td>Interface properties</td>
<td>Soil–Block</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>$\delta$, Friction Angle (°)</td>
<td>44</td>
</tr>
<tr>
<td>$\Psi$, Dilation Angle (°)</td>
<td>11</td>
</tr>
<tr>
<td>$C$, Cohesion (kPa)</td>
<td>-</td>
</tr>
<tr>
<td>$k_n$, Normal Stiffness (MN m$^{-1}$ m$^{-1}$)</td>
<td>100</td>
</tr>
<tr>
<td>$k_s$, Shear Stiffness (MN m$^{-1}$ m$^{-1}$)</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 4. Interface properties [26]*
Table 5. The maximum percentage reductions in wall facing deformation using cement-treated backfill compared with untreated backfill

<table>
<thead>
<tr>
<th>The number of reinforcement layers</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>The reduction of facing deformation (%)</td>
<td>64</td>
<td>73</td>
<td>74</td>
<td>75</td>
</tr>
</tbody>
</table>
Table 6. The maximum reduction in wall deformation using different reinforcement layers

<table>
<thead>
<tr>
<th>The number of layers</th>
<th>The percentage of reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement-treated backfill</td>
</tr>
<tr>
<td>From 3 to 4</td>
<td>44.5</td>
</tr>
<tr>
<td>From 4 to 5</td>
<td>27</td>
</tr>
<tr>
<td>From 5 to 6</td>
<td>24.5</td>
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</tbody>
</table>
Table 7. Comparison of the maximum percentage reduction of reinforcement force due to using cement-treated soil

<table>
<thead>
<tr>
<th>The number of reinforcement layers</th>
<th>The reinforcement layer number from bottom of wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30.94 40.63 85.81 - - -</td>
</tr>
<tr>
<td>4</td>
<td>82.3 45.8 82.34 89.95 - -</td>
</tr>
<tr>
<td>5</td>
<td>88.1 60.95 76.42 87.6 83.75 -</td>
</tr>
<tr>
<td>6</td>
<td>88.55 73.59 86.46 91.31 90.34 83.3</td>
</tr>
</tbody>
</table>