Numerical Investigation of Reinforced Soil Segmental Walls Using Two-Dimensional Finite Element Analysis in RS2

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Abstract. The FEM software RS2's efficiency in modelling an MSE wall was verified through numerical simulation of the significant structural components of a field-constructed MSE wall in Seattle, Washington. A 10.7-m high wall was simulated, and its performance was evaluated by plotting strain and load profiles for different geogrid reinforcement layers installed at various elevations. The simulation included modelling the backfill soil, which was compacted in stages under a compaction pressure of 8 kPa, along with three types of geogrid reinforcement layers installed with a spacing of 0.6 m. The wall's facing blocks, which were rigid modular blocks with a height of 0.2 m, were stacked in line with the backfill construction. All interfaces were modelled using an elastic-perfectly plastic model, and the model parameters were carefully selected from an accurately profiled field wall case study.

The results of the maximum and connection loads were compared with the corresponding measurements from the case under study. The longitudinal strain profiles were also predicted numerically and compared against a limited number of geogrid reinforcement layers. Overall, the comparisons were satisfactory, and RS2 demonstrated robust and versatile features in modelling such multi-feature geo-structures. This conclusion is valid, at least in the realm of serviceability conditions, as the strain levels in both the reinforcement layers and backfill soil remained below the serviceability limit states introduced by existing well-recognized construction codes.

Keywords: MSE wall · FEM · Geogrid reinforcement · Strain · Load

1 Introduction

Mechanically stabilized earth (MSE) walls have long been used to support different structures in the realm of geotechnical engineering. They have become a decent alternative to conventional rigid retaining walls for more than thirty years since their introduction

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to civil engineering projects. Retaining walls, bridge abutments, sea walls, commercial storage walls, and other structures are among their many uses. The main privilege of using MSE walls over conventional reinforced concrete walls are their ease of construction and expedited assembly of different constituent elements. It is also distinguishable from its conventional counterpart by not requiring formwork or curing; each reinforcement layer is structurally an autonomous element as it is laid, eliminating the need for support, scaffolding or cranes. An MSE wall is made up of facing elements, backfill soil, a foreslope providing toe restraint, and reinforcement layers that work together to form a gravity-retaining structure. The reinforcement layers are intermingled with the surrounding backfill soil to create a reinforced-soil mass. In most cases, the reinforcing layers are connected to the facing elements to form an overall integral system.

Design and analysis of MSE walls have been well covered in the literature of geotechnical engineering and design codes, especially in North America. However, with growing popularity of such walls in soil improvement projects in a variety of applications, more research is still underway. Different numerical analysis methodologies have been invoked to investigate the issue of load and strain distributions in congruent reinforcement layers along the segmented wall height. Examples of previous finite elements method (FEM) modeling of a geosynthetic reinforced modular block wall are the work of Ling and Liu (2009) and Rowe and Skinner (2001), who modeled an instrumented MSE wall. Later on, Huang et al. (2009, 2010), Yu et al. (2016), demonstrated comprehensive examples of modelling MSE walls using the finite difference method (FDM). More recently, Fathipour et al. (2021), and Mirmoazen et al. (2021, 2022), presented some limit load estimations for the reinforcement layers in a reinforced retaining wall using finite element limit analysis (FELA). However, their estimations exceeded far beyond the serviceability limit states. Additionally, Ardila et al. (2022) conducted some MSE modeling using RS2 software. Duncan-Chang and Mohr-Coulomb constitutive soil models were used to simulate the construction stages and surcharge loading application, showing the pertinence of these two constitutive models in the modeling of MSE structures.

In this study, the flexible features of the FEM software RS2 of Rocsicence were utilized to simulate a highly-instrumented tall MSE wall. The wall was built as a component of the approach fills for a bridge near Seattle, Washington. The measurements obtained from this project offer a corollary benefit in that the facing deformation and reinforcement strain measurements taken provide a distinctive chance to validate the accuracy of RS2 software estimations. This can be achieved by comparing the predicted and measured performance features.

2 Field MSE Wall

Figure 1 shows a cross-sectional view of the MSE Wall C, which was built to support the approach fill of a bridge that crosses the Cedar River. The construction of this wall, along with another one, was taken over by the Washington State Department of Transportation (WSDOT). To reinforce the wall, high-density polyethylene (HDPE) uniaxial geogrids were used in combination with modular block facings. Construction began in June 2004 and was completed in August 2006. The wall was instrumented to monitor reinforcement strains along with some other parameters in order to provide surveillance monitoring of the wall safety during and after construction. The wall is about 200 m long, deemed enough to warrant the veracity of a plane strain geometric idealization. The segmented wall height has been reinforced with three variations of HDPE geogrid reinforcement layers. The top five layers belong to Type 1, followed by three layers of Type 2 in the middle, and finally, the bottom nine layers are of Type 3. The stiffness properties of the geogrid reinforcement layers were found to vary with time and strain, according to a study by Yu et al. (2016), which presented a hyperbolic creep model for these types of reinforcements for an end of construction (EOC) period of 3,443 h. However, in the interest of simplicity, the reinforcement elements' creep behavior was intentionally disregarded, and they were assumed to have constant stiffness values that do not change with strain. A summary of the reinforcement properties for the three reinforcement types utilized in the construction of Wall C can be found in Table 1. In this table J_0 is the initial tangent modulus, χ is the empirical fitting parameter representing creep, and T_{ult} is the ultimate tensile strength of geogrid layers.

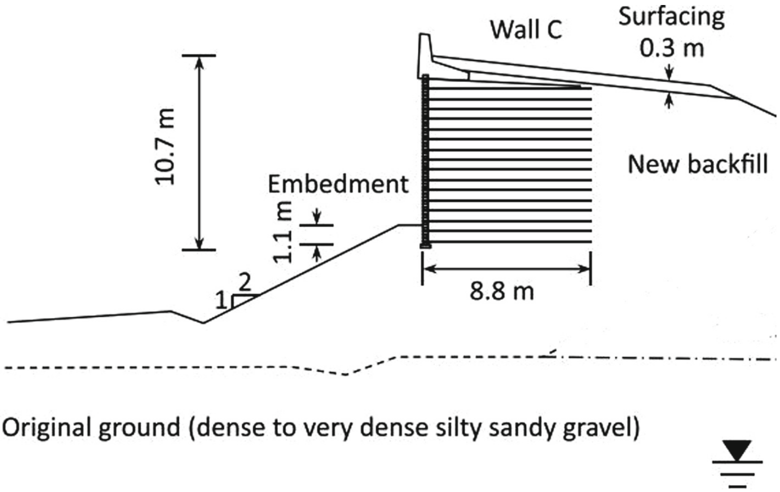

Fig. 1. Cross section view of wall C (adapted from Yu et al. 2016)

Table 1. Reinforcement parameters for EOC of 3,443 h adopted from Yu et al. (2016)

Type	Material	J_0 kN/m	χ m/kN	T_{ult} kN/m	Thickness mm	Coverage ratio (Rc)
1		525	3.26×10^{-2}	54	2	0.94
2	HDPE	597	3.59×10^{-2}	70.3	2	0.94
3		1088	9.58×10^{-2}	115	2	0.94

3 RS2 Numerical Modelling

An MSE wall is a type of retaining wall that is constructed using engineered fill material that is reinforced with geosynthetic materials. When it comes to numerical modelling of an MSE wall, several important elements must be considered. These elements include:

1. Soil Properties: The properties of the soil that will be used to construct the MSE wall are essential to consider when modeling it. These properties include parameters such as soil density, shear strength, and stiffness. They are critical to accurately simulating the behavior of the wall under different loading conditions. However, Huang et al. (2009) and Ardila et al. (2022) supported the adequacy of the basic linear elastic-plastic Mohr-Coulomb constitutive model in comparison to more complex models, at least as long as the EOC condition is concerned. Table 2 summarizes the backfill soil properties, as well as other essential parameters that will be discussed shortly.

2. Reinforcement Properties: The properties of the geosynthetic reinforcement material used in the wall are also crucial. The properties to be considered here include strength, stiffness, and the ability to withstand deformation. The reinforcement material is used to provide additional stability to the wall and to resist lateral loads. To simplify matters, the no-creep properties listed in Table 1 have been adopted.

3. Facing Properties: The MSE wall was constructed from 50 articulated rigid facing blocks. Each block has a width of 30 cm and a height of 20 cm. The blocks were stacked vertically on top of each other to form the wall. The properties to characterize the facing blocks in the numerical model are presented in Table 2, including the block-block and soil-block joints' properties.

4. Wall Geometry: The geometry of the MSE wall, including its height, slope, and overall shape, must be accurately modeled. The shape and geometry of the wall can affect its stability and performance under different loading conditions. A segmented wall with a height of 10.7 m, as illustrated in Fig. 2, was simulated in RS2.

5. Loading Conditions: The loading conditions that the MSE wall will be subjected to must be accurately simulated. It is important to consider both the self-weight of the backfill and any transient compaction loads when analyzing the stability of an MSE wall under static loading. The self-weight of the backfill will create a permanent pressure on the wall, while the transient compaction load will create additional horizontal pressure on the facing panels and the connecting reinforcing layers due to the compaction effort during staged construction. However, it is worth noting that the compaction pressure is removed after each layer construction, which means that it is not a permanent load on the wall. Nonetheless, during the construction process, the compaction pressure can be significant and should be accounted for in the analysis of the wall to ensure that it can withstand these loads and maintain stability. Overall, when analyzing the stability of an MSE wall under static loading, it is important to consider all of the loads that will act on the wall over its expected service life, including both permanent and transient loads, to ensure that the wall is designed to withstand all potential loads and remain stable. In the current study, a compaction effort of 8 kPa, applied uniformly over the width of each layer, is assumed according to Hatami and Bathurst (2006).

6. Connection Details: The connection details between the reinforcement layers and the facing panels of the wall should be considered when modeling the wall. The way in which the connection load is compared to the maximum reinforcement loads depends on

Table 2. Soil and interface constitutive parameters in RS2 simulations (Yu et al., 2016)

Parameter	Value
Backfill soil	
Unit weight (kN/m3)	21.7
Young's modulus (MPa)	80
Poisson's ratio	0.3
Friction angle (°)	54
Dilation angle (°)	14
Cohesion (kPa)	2
Facing blocks	
Unit weight (kN/m3)	24
Young's modulus (GPa)	32
Poisson's ratio	0.15
Interfaces	
Block-Block	
Cohesion (kPa)	58
Friction angle (°)	36
Normal stiffness (MPa/m)	1,000
Shear stiffness (MPa/m)	40
Soil-Block	
Normal stiffness (MPa/m)	100
Shear stiffness (MPa/m)	1
Soil-Reinforcement	
Cohesion (kPa)	2.51
Friction angle (°)	43
Grout Shear stiffness (MN/m/m)	1

these specific details. For the purpose of this study, the reinforcement layers situated at different elevations are secured to the internal upper corner of the facing panels, which accurately represents the actual construction condition.

7. Analysis Method: The method used to analyze the behavior of the wall should also be considered. Common analysis methods include limit equilibrium analysis, finite element analysis, and finite difference method. RS2 utilizes the finite element method to model various solid and structural components of an MSE wall. The software achieves this by discretizing the backfill continuum into either three or six-node triangular zones and by utilizing linear two-node geogrid elements to simulate the reinforcement layers.

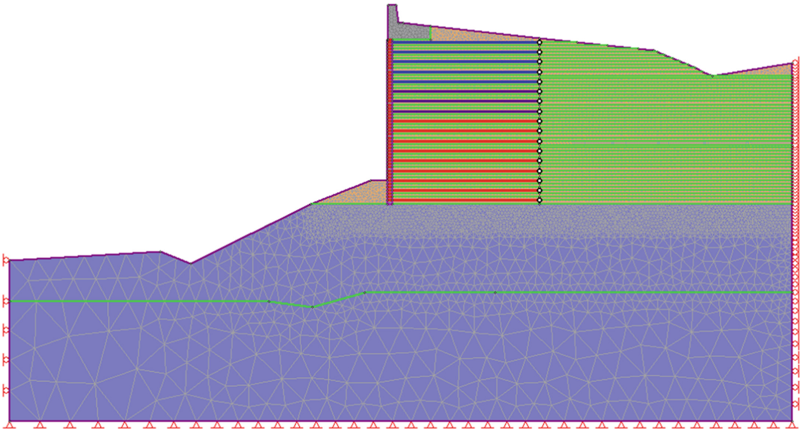

Fig. 2. Cross section of the numerical modelling in RS2

8. Joints and Interfaces: The MSE wall system's different parts are interconnected using the interface and joint definition provided in RS2. Specifically, the geogrid reinforcement elements interact with the surrounding backfill soils through Coulomb-type interface elements. To determine the shear strength components of these interface elements, a reduction factor is applied to the corresponding properties of the surrounding soil. Yu et al. (2016) assumed a reduction factor of 2/3. Similar assumptions were made for the interface between the backfill soil and the facing blocks. The utilization of shear keys (connectors) aided in the alignment of the blocks and bolstered the interface shear capacity among the modular block units. Consequently, the block-block interfaces were assigned higher values for shear strength properties, as demonstrated in Table 2.

By taking into account these elements in numerical modeling, an accurate simulation of the behavior of an MSE wall can be achieved, allowing engineers to design safe and efficient retaining walls.

4 Results

RS2 software generated various types of output based on the FEM analyses conducted, including load and strain profiles for different reinforcement layers along the height of the wall, as well as the horizontal displacement of the wall facing. The latter can be interpreted in two ways: as either out-of-alignment or moving datum displacement profiles. Due to brevity, we will not delve into a discussion on the wall facing displacement profiles. Instead, we will focus on examining the geogrid reinforcement layers in terms of their longitudinal strain profiles, as well as the maximum and connection load values for each layer. Finally, we will compare the predicted values with the measurements obtained by Yu et al. (2016). In addition, assessing the total maximum shear strain within the backfill soil and the highest strain of reinforcement will help determine how close the stress condition within the backfill is to the serviceability limit state specified in AASHTO (2020).

Figure 3 compares the maximum predicted load values obtained from RS2 analysis with those measured during the construction of Wall C, as described earlier. The results show that RS2 is an effective numerical analysis tool for simulating the behavior of MSE walls under working conditions. The maximum reinforcement load values closely match the measurements taken along the height of the wall. Interestingly, the trend depicted in Fig. 3 indicates that the global maximum reinforcement load value does not occur at the lowest level, as expected by the conventional AASHTO simplified approach. The restraining action of the toe backfill causes a substantial decrease in the load of the reinforcement layers at the bottom. As a result, the maximum reinforcement load values adopt a trapezoidal pattern of variation, as depicted in Fig. 3. According to the projections, the highest load value for the entire structure will occur within the central third of the wall's height.

In Fig. 4, a graphical representation of the longitudinal strain profile for several geogrid layers is provided, and these graphs are compared to their corresponding measurements. The purpose of this comparison is to assess the accuracy of RS2 in replicating the strain values that are mobilized along the length of geogrid reinforcement layers.

Upon analyzing the data, it appears that RS2 performs well in reproducing the strain values, indicating that the software is robust enough to simulate the behavior of geogrid reinforcement layers accurately. Additionally, the results in Fig. 4 indicate that the maximum reinforcement strain values occur slightly further away from the connection point. This observation aligns with the existing literature on this subject.

In summary, Figs. 3 and 4 provide evidence that RS2 is a reliable tool for simulating the behavior of geogrid reinforcement layers, and its results are in good agreement with what is expected based on previous research.

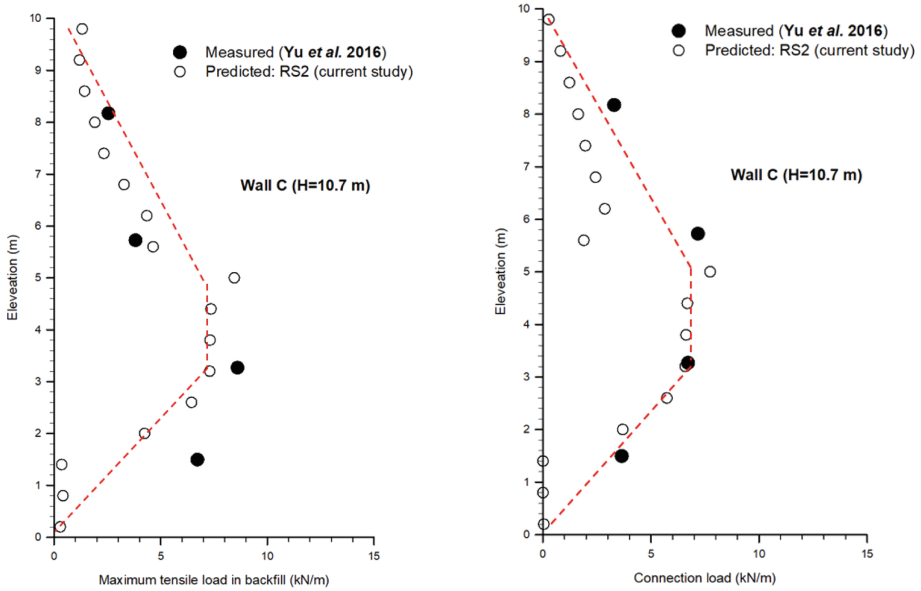

Fig. 3. Schematic illustration of the load-displacement test data along with the hyperbolic model

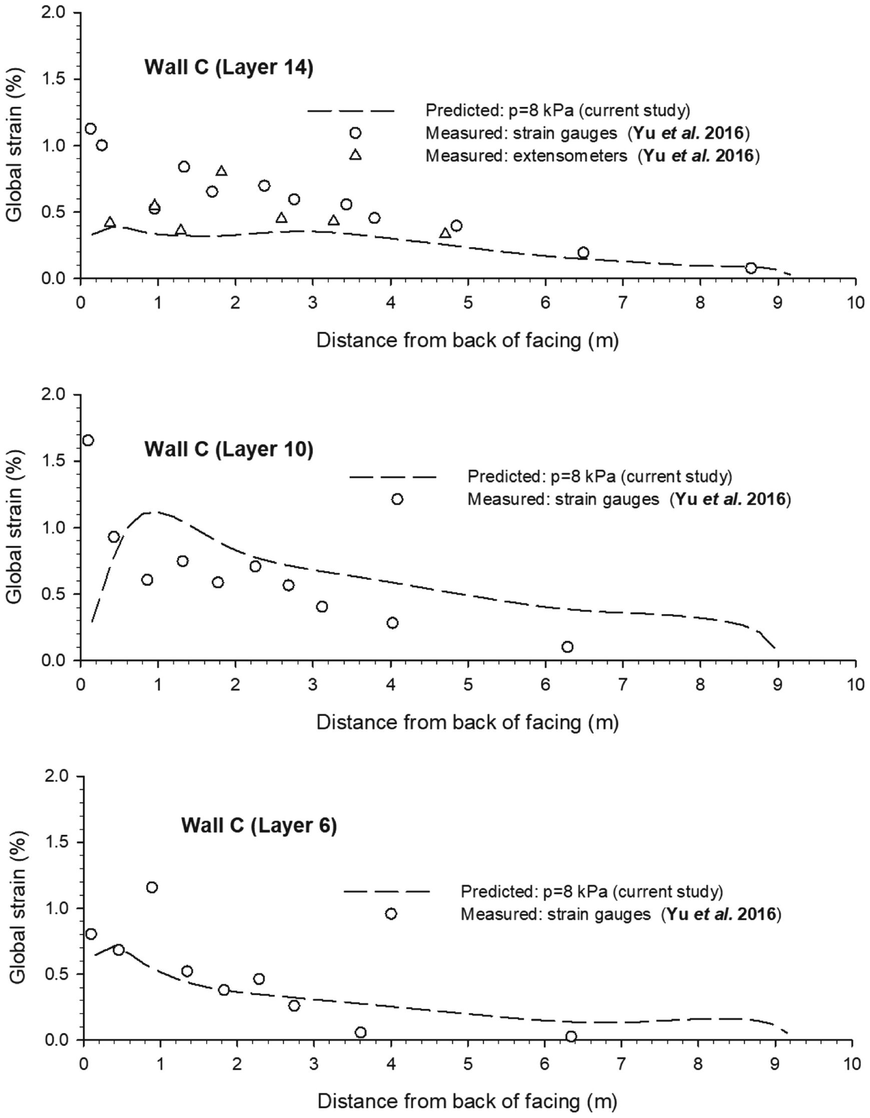

Fig. 4. Schematic illustration of the reinforcement strain along the length of different layers

The serviceability limit state related to reinforcement strain level is typically expressed in terms of the maximum allowable strain in the soil and reinforcement elements. Excessive strain in the reinforcement can cause it to deform or even break, which can compromise the stability of the wall. The maximum allowable reinforcement strain level is also typically specified in the design criteria and is often around 2% to 3% according to AASHTO (2020). It should be emphasized that the threshold values for shear strain of backfill soil and strain of reinforcement may differ based on design specifications and applicable building codes. Nevertheless, the data presented earlier on

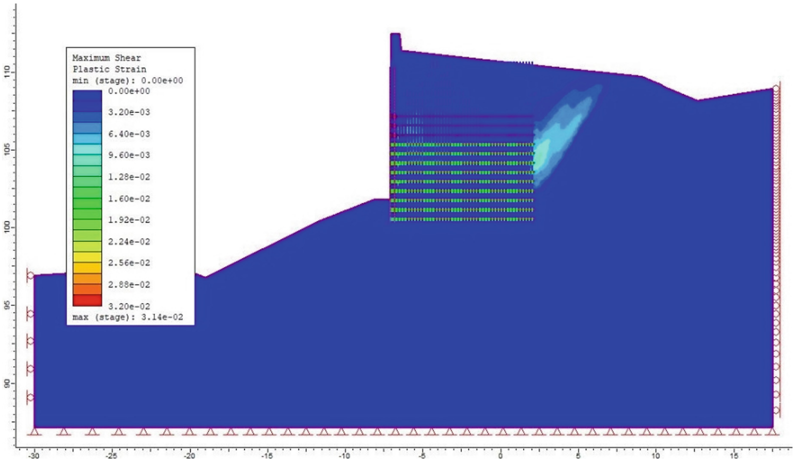

Fig. 5. Shear strain increments contour plots acquired from RS2 analysis

the load and strain of reinforcement layers supports the close correspondence between the maximum reinforcement load/strain and the shear strain generated in the adjacent backfill soil as demonstrated in Fig. 5.

5 Conclusions

The article discussed the use of the FEM software RS2 to model an MSE wall in Seattle, Washington. The simulation involved modeling the significant structural components of the wall, including the facing blocks, backfill soil, and geogrid reinforcement layers installed at various elevations. The study evaluated the wall's performance by plotting strain and load profiles for different reinforcement layers. Due to the lack of accurate facing displacement measurements for the case study under evaluation, no displacement profiles were reported.

The simulation involved compacting backfill soil in stages using a compaction pressure of 8 kPa. The study deployed three types of HDPE geogrid reinforcement to install 17 layers of reinforcement with a spacing of 0.6 m. The performance of these reinforcements was evaluated by analyzing the maximum and connection loads with depth and comparing them to values obtained from a field wall case study. The model used an ideal Coulomb model to represent the soil-reinforcement, soil-facing block, and block-block interfaces, which helped to limit the resistance mobilized in the elastic interface springs. The model parameters were carefully selected based on the field wall case study.

The simulation results were meticulously compared to a number of load measurements for geogrid reinforcement layers, and numerical predictions were also made for the longitudinal strain profiles. The results of the comparison were satisfactory and confirmed the trapezoidal shape of the maximum and connection reinforcement load variations with the wall height. As a result, the study concluded that RS2 demonstrated robust and versatile features for modeling such complex geo-structures. However, it is important to note that this conclusion only applies to serviceability conditions since the strain levels in both the reinforcement layers and backfill soil were kept below the serviceability limit states introduced by AASHTO standards.

Overall, this study provided an overview of the use of RS2 software to model a complex MSE wall problem and evaluate its performance. The study highlighted the importance of careful selection of model parameters and the use of appropriate interfaces between different components to obtain accurate results. The study also underscores the need to ensure that the design of MSE walls complies with the serviceability limit states outlined in construction codes to ensure their long-term performance.

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