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A Numerical Study on Effect of Site Conditions on Connection Load in Geosynthetics-Reinforced Soil Wall

Adarsh Kumar[1#], and *Amit* Prashant[2]

[1]*M. Tech Student, Indian Institute of Technology Gandhinagar, Discipline of Civil Engineering, Gandhinagar, India*
[2]*Professor, Indian Institute of Technology Gandhinagar, Discipline of Civil Engineering, Gandhinagar, India*
[#]*adarshkumar@iitgn.ac.in*

ABSTRACT

Geosynthetics-reinforced soil (GRS) walls have gained immense popularity among other reinforced soil walls. In recent times, case studies have highlighted several GRS walls facing problems such as cracking on the facia, breakage of connection pins in the segmental block, breakage of connection between facia and reinforcement, and relative settlement between facia and backfill, all leading to the serviceability issues or failure of the wall. The existing design methods estimate connection loads using laboratory pull-out tests, which do not incorporate the effect of on-site conditions, such as differential settlement, compaction-induced stresses, and facia geometry, and the stress mobilization in the connection system. This study examines the stress distribution in the facia connection system of segmental reinforced soil walls subjected to site conditions such as inadequate backfill compaction and differential settlement between facia and backfill. A finite element (FE) approach has been adopted to predict the stresses in the reinforcement for the connection loads in the reinforcement-facia connection system subjected to the above-mentioned conditions. The modular block facia, along with geogrid reinforcement connections, was studied, incorporating appropriate geometrical and interface properties (viz. geosynthetics-block interfaces). Based on the study, the obtained variation in the von Mises stresses in the geogrid, embedded in the modular block, due to connection load at the service state was analysed. A comparative analysis of the performance of three different segmental block facia-reinforcement connections was also performed to understand their suitability in a particular site condition.

Keywords: GRS wall; numerical modelling; segmental retaining walls; reinforcement connection load; FEM.

1. Introduction

Geosynthetics-reinforced soil (GRS) walls are widely constructed owing to their cost-effectiveness and aesthetics. Among these, segmental retaining walls with precast modular (concrete) block facing have gained popularity worldwide in the last four decades because of their ease of construction and commendable performance. They mainly consist of three elements: the facing system, the geosynthetic reinforcement, and the soil. This study focuses on the interaction between manufactured elements of the segmental retaining wall, i.e., the facing and geosynthetic reinforcement. Most of these walls have been built using polymeric geogrids as reinforcements, placed between the modular blocks to form a frictional-cum-mechanical connection (Soong and Koerner 1997; Bathurst, Althoff, and Linnenbaum 2008). The small size of the modular blocks and the flexible nature of such walls allow complex geometry at different heights and several levels under adverse site conditions. However, recent field investigations have revealed that connection instability has been one of the major causes of the failure of segmental retaining walls (Shin et al. 2011; Xiao et al. 2021). Researchers have also highlighted that instability in such walls occurs due to poor connection strength and/or inadequate connection systems (Buttry et al. 1993; Guier et al. 2009; Huang et al. 2010; Hatami, Grady, and Ulmer 2009; Bathurst, Althoff, and Linnenbaum 2008; Soong and Koerner 1997)

The modular block selection and design depend upon block geometry, the manner in which the blocks fit together, block material properties, and aesthetics (Allen 1993). These parameters affect the facing stiffness, stability, and stress distribution. Nonetheless, the present guidelines do not provide procedures to determine the minimum dimensions and block geometry required to ensure the facing stability and connection performance at the service state conditions. The general practice is to establish a block geometry that prevents geosynthetic reinforcement pullout from the facing blocks. A pullout test under standard laboratory conditions is used to ensure the same. However, this does not focus on understanding the stress distribution in the connection system owing to the mechanical advantage introduced in block geometry and site conditions, such as differential settlement and compaction-induced stresses. Past researchers have tried to study the connection strength and stability of segmental blocks based on laboratory experiments (Buttry et al. 1993; Bathurst and Simac 1993; Soong and Koerner 1997). However, these studies mainly focused on determining connection strength and its variation with surcharge load. A detailed numerical study of the GRS wall connection system under critical field conditions is essential to understand the response of its various components. It can provide handy insights into the design of the geometry and dimensions of the connection systems within time and resource constraints. Although many numerical studies have been performed to see the overall performance and internal stability of the GRS wall (Mohamed, Yang, and Hung 2014; Zhang and Chen 2023; Yoo 2018), little effort has been made to understand the stress mobilization in a particular connection system subjected to site conditions using numerical methods.

This study aims to understand the stress distribution mechanisms in the reinforcement-facia connection systems under service state conditions using numerical methods. The FE method is a widely used numerical method for modelling GRS walls (Hatami and Bathurst 2005; 2006; Liu 2009). It offers a comprehensive analysis of stress and strain at any location of interest. (e.g., at the nodes). Thus, 3D modelling using the finite element method (FEM) has been employed in this study. The study captures the influence of modular block geometry and the type of geosynthetic−facing unit interface (i.e., continuous keys or lips) on stress mobilization in the connection system. It also highlights the effect of differential settlement and compaction-induced stresses on the stress distribution in the connection system.

2. Numerical Modelling

2.1. Reinforcement-facia connection system model and boundary conditions

The ABAQUS CAE software program was used to carry out numerical analysis. A set of simple models were adopted in the current study, as described in the later sections, to understand the stress distribution in the connection system of segmental retaining walls using modular block and geogrid.

The 3D modelling is well suited to analyse the reinforcement facia connection systems with mechanical elements such as shear keys, pins, and clips. In this paper, the modular block connection systems with shear keys or lips were modelled and analysed. The properties and dimensions of the modular block were chosen from previous studies conducted in the laboratory (Buttry et al. 1993; Bathurst and Simac 1993). The dimensions (height (h) x width (w) x depth (d)) of the modular block used for the base case study were 15 cm x 41 cm x 30 cm (Fig. 1) (Buttry et al. 1993). The geogrid reinforcement was modelled as a continuous layer. Each component was modelled in three dimensions using solid, homogeneous, and deformable elements. A detailed description of the geometry and properties has been mentioned in subsequent sections. The boundary conditions were modelled wherein the lower horizontal face of the lower block was restrained in all directions, whereas the vertical face of the upper block was restrained only in the plane with normal along the axis of the pull-out load application. The width of the geogrid, sandwiched between the modular blocks, was kept equal to that of the modular block for simplicity in analysis. However, the free length of the geogrid was restricted to around 200 mm to avoid local effects and uniform stress application on the connection (Buttry et al. 1993; Bathurst and Simac 1993). The 2D view of the model, along with boundary conditions and load directions, is illustrated in Fig. 2.

The boundary conditions, contact interfaces, normal load, and pull-out load in the finite element numerical model were applied in stages. A total of four steps were used in the modelling, including the initial step. The boundary conditions were applied in the initial step. The contact interface properties were established in the next step, followed by applying normal load on the top block. In the final step, the pull-out force was applied to the geogrid. The effect of the rate of loading was not studied in this paper, although it affects the stress distribution (Buttry et al. 1993; Bathurst and Simac 1993). The time step for the application of pull-out load was kept constant for all cases. Also, this study did not simulate the effects of differential settlement of the reinforced backfill soil layers and compaction-induced stresses on geogrid directly. However, a vertical load was applied on the geogrid in the final step, along with the pull-out load, to simulate the effect of differential settlement and compaction-induced stresses.

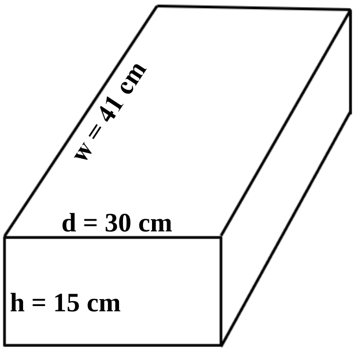


Figure 1. Dimensions of modular block for base case study

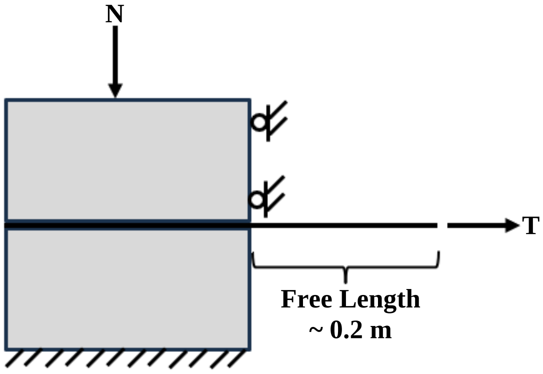


Figure 2. 2D view of the model with boundary conditions

2.2. Modular block model and material properties

The segmental concrete modular block-facing elements were used in the study. It was modelled as linear elastic material using Hooke’s law. The properties of the concrete were taken similar to previous studies (Eddine and Mekki 2021; Damians et al. 2021). The assigned properties have been presented in Table 1. Blocks of three different geometries, commonly used in construction, were used in the study (Fig.3). The dimension of each block type is specified in Table 2. In the finite element analysis, eight-noded hexahedra elements (C3D8R) were used for the meshing of solid modular blocks.

Table 1. Modular block material properties

Parameters	Value
Modular Block	
Young's modulus (MPa)	30000
Poisson's ratio	0.3
Density (kg/m^3)	2400

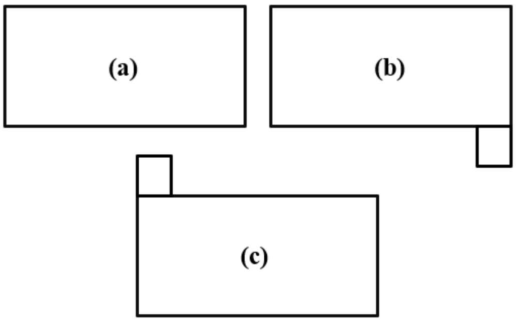


Figure 3. Typical facing blocks cross-section: (a) Modular block (Type I) (b) Modular block with trailing lip (Type II) (c) Modular block with leading lip (Type III)

2.3. Reinforcement model and material properties

In this study, a polyester biaxial geogrid reinforcement layer was used as reinforcement. It was modelled using homogeneous solid sheet, without apertures, considering isotropic elastic material. As the geogrid is sandwiched between the solid concrete blocks, the interlocking effect will not be observed. Hence, the assumption to model the geogrid as a sheet simplifies the modelling without affecting the behaviour significantly. The properties of the geogrid used in finite element analysis were chosen by referring to the previous literature and have been specified in Table 2 (Won and Langcuyan 2020; Damians et al. 2021; Eddine and Mekki 2021). The geogrid reinforcement layer was meshed using eight-noded hexahedra elements (C3D8R) for the numerical simulation.

Table 2. Geogrid material properties

Parameters	Value
Geogrid	Biaxial
Young's modulus (MPa)	1500
Poisson's ratio	0.3
Density (kg/m^3)	900
Thickness (mm)	5

2.4. Interface model and properties

Proper modelling of interfaces in the connection system is a critical aspect to accommodate sliding and separation behaviour between dissimilar components. The numerical studies conducted previously, in general, focused on the performance of the GRS walls as a whole and tend to define suitable interface properties to simulate the soil-geosynthetic and block-block interfaces (Hatami and Bathurst 2005; Won and Langcuyan 2020). But hardly any attempt has been made to understand the stress-mobilisation in the connection system using numerical modelling. However, previous researchers have highlighted that failure can happen due to facing stability (Simac et al. 1993; Bathurst, Kk, and Simac 1994). Accordingly, the surface-to-surface contact interaction was used to define interfaces between block and reinforcement in this study. The choice of master and slave surfaces to simulate interface behaviour is highly subjective (Laursen and Simo 1993; El-Sawy and Moore 1996). In this study, the geogrid surfaces were chosen as the master surface whereas modular block surfaces were chosen as slave surfaces (Fig. 4). The modular block surfaces, being slave surfaces, were meshed with finer mesh size with respect to the mesh size of geogrids.

The interface between the geogrid surface and the modular block surface was assumed to be frictional in the tangential direction, while in the normal direction, the interfaces were defined as "hard contact" and separations were allowed after contact. The Mohr-Coulomb frictional model with a linear failure envelope was employed to define frictional interfaces. The choice of interface parameters used in the study was based on references from previous studies (Bergado and Jin-Chun Chai 1994; Damians et al. 2021; Cai and Bathurst 1996). A friction coefficient of 0.3 was assumed as a conservative value for geogrid interaction with concrete referring to past literature.

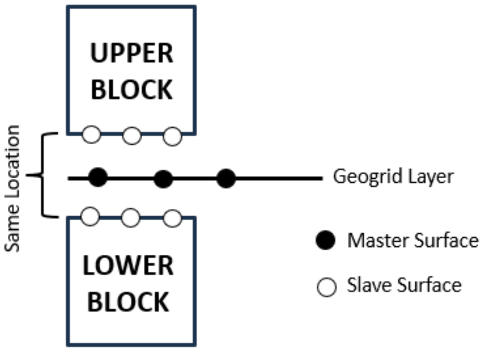


Figure 4. Interfaces showing master surface and slave surface for contact elements

3. Results and Discussion

In this paper, our interest is to evaluate and analyse the influence of facia geometry introduced for the mechanical advantage (shear key or lip) and site condition on stress distribution in reinforcement facia connection systems numerically, using the finite element software program ABAQUS CAE. The influence of the shear key introduced in modular block geometry was studied using three configurations (types) of blocks depending upon the position of the shear key introduced in them for mechanical advantage (Table 3). The base case modular block (without any shear key) was deliberately chosen in dimensions similar to the ones used in field applications to simulate real problems. The type II modular block had a continuous shear key at the face towards the GRS wall (trailing end) in the downward direction. In contrast, the type III modular block had a continuous shear key of the same dimensions as that of type II, but at the face away from the wall (leading lip) and in the upward direction.

Table 3. Dimensions of modular blocks

Block Type	Height (cm)	Width (cm)	Depth (cm)	Lip Dimension (cm x cm)
Type I	15	41	30	-
Type II	15	41	30	3 x 2.5[a]
Type III	15	41	30	3 x 2.5[b]

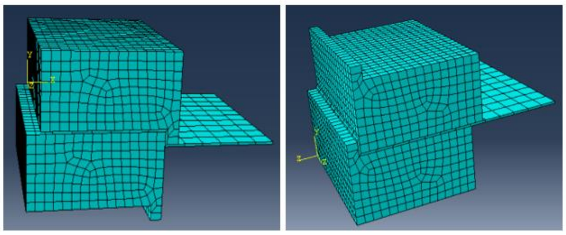
a: Trailing lip
b: Leading lip

3.1. Effect of Block Geometry

The geogrid-facia connection system was modelled using type I block (base case) and geogrid using the setup in Fig. 2. A normal load (N) of 13 kPa was applied to the base case, as chosen in the laboratory study of Buttery et al. 1993. It was followed by the pull-out load (T), which was applied to the geogrid. The relative movement of the embedded length of the geogrid with respect to the concrete blocks was recorded. This relative movement of the embedded length was called the connection deformation (Buttery et al. 1993). In this study, the pull-out load corresponding to a serviceability deformation of 19 mm was defined as the failure load for the connection system under serviceability conditions, similar to the criteria adopted by Buttery et al. 1993. This load was found to be 2.46 kN/m (a uniform pressure of 492 kPa applied normally on the 5 mm thick geogrid surface) for the base case connection system.

The type II and III concrete modular blocks had a continuous shear key (lip) at the trailing and leading edge, respectively, for the mechanical advantage thereby arresting connection deformation. The reinforcement-facia connection systems were modelled using the same setup and boundary conditions as for the base case (Fig. 2), with modular block types II and III. The orientation of the blocks and geogrid in both cases is shown in Fig. 5. A uniform pressure of 492 kPa was applied normally on the 5 mm thick geogrid surface, obtained corresponding to 19 mm deformation for the base case. The von Mises stress distribution along the length of the geogrid and connection deformation were recorded for both the cases. It was found that the geogrid embedded behind the shear key in connection systems with type II and III modular blocks had negligible connection deformation vis-à-vis 19 mm for the base case. This might be due to the introduction of the shear key for mechanical advantage. However, the von Mises stress distribution in the geogrid along its embedded length in the direction of pull-out load (true length) corresponding to 2.46 kN/m of pull-out load, in each of the three cases shows that the geometry introduced in modular block for mechanical advantage has a significant effect on the stress distribution in the connection system when subjected to pull-out load (Fig. 6). It was observed that the type I connection system had the least value of stress, and the type II connection showed a spike in stress at the shear key. This could be because in type I the connection deformation in the absence of a shear key provided a smooth distribution of stresses. However, in type II, it was arrested by the shear key at the trailing end, below the block, leading to stress concentration.

This exercise was further extended to the type II and III connection systems by applying a pull-out of 4 kN/m (around 1.6 times 2.46 kN/m) to observe von Mises stress mobilization in the connection systems at higher loads. The simulation results showed that in type III connection system, most of the geogrid embedded in the connection system actively participated in stress distribution by mobilization of friction, but this was not the case in type II (Fig. 7). This might be due to the shear key at the leading edge in type III, which allowed the geogrid to mobilize friction. In contrast, in type II, the geogrid embedded behind the shear key did not participate much in friction mobilization.



(a) **(b)**

Figure 5. Orientation of blocks and geogrid using (a) type II (b) type III connection

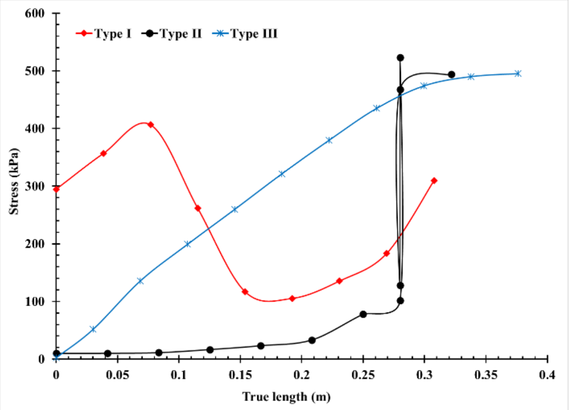


Figure 6. Stress distribution in connection systems at pull-out load of 2.46 kN/m

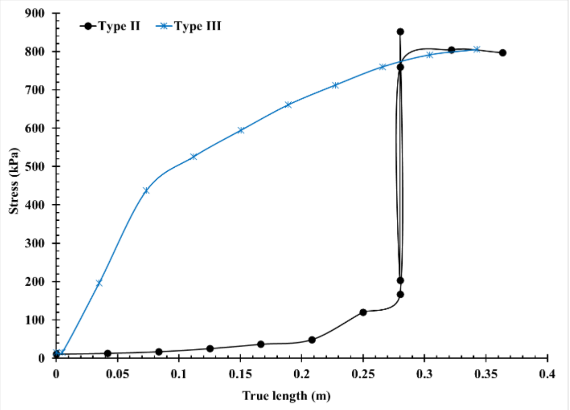


Figure 7. Stress distribution in connection systems at pull-out load of 4 kN/m

3.2. Effect of Site Conditions and Block Geometry

The site conditions, such as differential settlement between reinforced backfill and facia, and the compaction-induced stresses affect the load acting on the reinforcement-facia connection system and, thus, the performance of the connection system. The earlier studies in which compaction-induced stresses were modelled had applied either a uniform vertical stress only on the top of each soil layer (Hatami and Bathurst 2005; Guler, Hamderi, and Demirkan 2007; Yu et al. 2016; Yu, Bathurst, and Allen 2017) or an equally distributed load at top and bottom of each soil layer (Mirmoradi and Ehrlich 2015; Scotland et al. 2016). In this study, as the soil elements were not modelled, the effect of differential settlement and compaction-induced stresses along with block geometry was studied by applying a uniform vertical stress of 2.7 kPa (vertical stress of 0.15 m of soil layer with unit weight of 18 kN/m^3) on the geogrid reinforcement, along with the pull-out load of 4 kN/m on type II and III connection systems. Fig. 8 shows that the stresses in the connection systems are significantly higher (Type II C and Type III C) when subjected to vertical load along with horizontal pull-out load compared to only pull-out load (Type II and Type III). It was also observed that this stress was more prominent in the type II connection systems as compared to type III, which highlights the fact that the position of the shear key in the modular block has a significant effect on stress mobilization in the connection system.

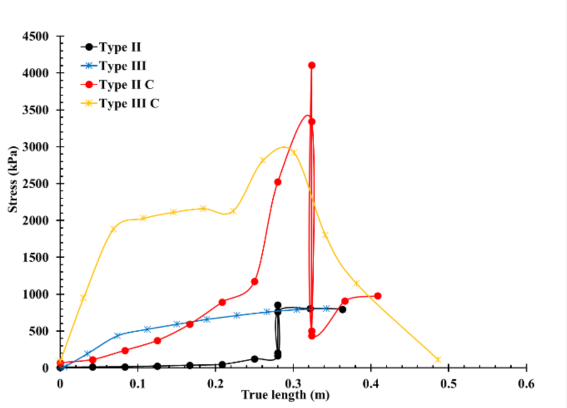


Figure 8. Stress distribution in connection system due to applied vertical load along with pull-out load

Conclusions

This paper attempts to highlight the effects of the geometry of facia and site conditions on stress mobilization and connection load in modular block-geogrid reinforcement connection systems. The 3D FEM model was used to predict the influence of block geometry and site condition on the performance of the connection system. The study demonstrates that the geometry introduced in facing elements for mechanical advantage can arrest the connection deformation. But stress mobilisation and concentration may increase the chances of breakage of geogrid connection or facing instability.

However, the modelling approach adopted in this study has limitations, such as the uniform vertical stress being directly applied to the reinforcement to understand the behaviour of the connection system under compaction-induced stresses and differential settlement. Also, geogrid has been modelled without apertures. An elaborate modelling approach, along with simulating site conditions, will be adopted in further studies.

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