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Effects of facing, reinforcement stiffness, toe resistance, and height on reinforced walls

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A B S T R A C T

This study numerically investigated the combined effect of reinforcement and facing stiffness, wall height, and toe resistance on the behavior of reinforced soil (RS) walls under working stress conditions. For RS walls with vertical segmental block facing, parametric analyses showed that the combined effect of the facing stiffness, wall height, and toe resistance on the distribution of the maximum reinforcement load with depth may be limited to approximately 4 m above the base of the wall. Furthermore, the shape of the distribution of the reinforcement load may be a function of the combined effect of the wall height, reinforcement stiffness, toe resistance, and facing stiffness. For a given facing stiffness and fixed-base conditions, increasing the height of the wall and reinforcement stiffness may change the distribution shape of the reinforcement load from trapezoidal to the triangular. Additionally, the maximum reinforcement loads calculated using finite element analyses were compared to the values predicted by design methods found in the literature. Some limitations of those design procedures are presented and discussed.

1. Introduction

Several factors control the behavior of reinforced soil walls including wall heights, surcharge loading, foundation conditions, facing types and inclination, reinforcement types and stiffness, reinforcement spacing, backfill soil characteristics, backfill soil compaction-induced stress, and toe resistance. In recent decades, several experimental and numerical investigations have been carried out to determine the influence of these factors on wall performance. Although individual assessment of these factors is important, their combined effects are also required to better understand the wall behavior.

The importance of facing stiffness was discussed by Tatsuoka (1993), Tatsuoka et al. (1997), and Bathurst et al. (2006). They have shown that stiffer facing reduces the reinforcement loads in GRS walls. The impact of toe resistance was analytically considered by Leshchinsky and Vahedifard (2012) in reinforced masonry block walls. They showed that the reinforcement load increases significantly when toe resistance vanishes. Huang et al. (2010) studied the combined effects of the block–block interface stiffness and toe resistance using the finite difference fast Lagrangian analysis of continua (FLAC) codes (Itasca, 2005), and found that increasing the block–block interface stiffness and toe stiffness reduces the load in the reinforcement and increases the toe load. Ehrlich and Mirmoradi (2013) and Mirmoradi and Ehrlich (2014b, 2016a) considered the effect of facing stiffness with a combination of the toe resistance using physical models supported by FEM analyses. They concluded that the effect of facing on the magnitude of the summation of the reinforcement load is not solely associated with facing stiffness. Rather, it is associated with the mobilized shear stress at the base of the facing columns and the foundation soil. Using the analogy of interface shear springs between blocks and between the base of the wall and the foundation, Bathurst et al. (2007) demonstrated the combined influence of the facing stiffness and toe resistance on reinforcement loads. In sum, these findings draw attention to the importance of the combined effect of the facing stiffness and toe resistance on the behavior of reinforced soil walls. Note that the analysis performed by Leshchinsky and Vahedifard (2012) was accomplished using reinforcement strength-based methods, while the others were based on a reinforcement stiffness approach. Strength-based methods are best for ultimate limit states, while stiffness methods better represent the working stress conditions.

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Wall height is another controlling factor that may be considered in combination with the facing stiffness and toe resistance. Mirmoradi and Ehrlich (2015a) numerically evaluated the influence of this combination in geosynthetic reinforced soil walls using the summation of the maximum load in the reinforcement layers, $\sum T_{max}$, which is important for evaluation of wall behavior in a global sense. However, the individual T_{max} value in each reinforcement layer has not been properly addressed considering this combination. Evaluation of T_{max} in the reinforcement layers is one of the major objectives in the design of RS walls.

In this study, the combined effect of the facing and reinforcement stiffness, toe resistance, and wall height are investigated for each reinforcement layer based on the numerical modeling performed by Mirmoradi and Ehrlich (2015a). The FEM modeling is extended to consider the steel reinforcements as well as the geosynthetic reinforcement. Additionally, the prediction capabilities of the AASHTO simplified (2014), Ehrlich and Mitchell (1994), K-stiffness (Allen et al., 2004; Bathurst et al., 2008), and simplified stiffness (Allen and Bathurst, 2015) design methods are evaluated.

2. Model validation

Numerical modeling was performed using the two-dimensional finite-element (FE) computer program PLAXIS 8 (Brinkgreve and Vermeer, 2002). Here, the plane-strain model was used. Numerical modeling was first validated against data from a full-scale reinforced soil wall (Wall 1) built at the Royal Military College of Canada (RMC) (Hatami and Bathurst, 2005). The wall was 3.6 m high with a facing inclination of 8° to the vertical. The length and the vertical spacing of the geogrid were 2.52 m and 0.6 m, respectively. The hardening soil (HS) model was applied.

Reinforcement was modeled as a linear-elastic material with perfect interface adherence to the adjacent soil. For the block–-block and soil–block interfaces, the same parameters used by Guler et al. (2007) were employed. Fifteen-node triangular elements were used to model the soil layers and other volume clusters, and a fine mesh was used to divide the system into discrete segments for study.

The wall was constructed in stages; i.e., 0.15 m thick soil lifts were placed and compacted until the final wall height was reached. Compaction-induced stress was modeled by applying an 8 kPa distribution load at the top and bottom of each soil layer. Details about this compaction modeling procedure can be found in Mirmoradi and Ehrlich (2014a, 2015b).

A fixed boundary condition was employed in the horizontal direction on the right lateral border. At the bottom of the model, a fixed boundary condition in both the horizontal and vertical directions was applied, except at the base of the block facing; at this point, a roller was modeled to allow only horizontal displacement. The toe was horizontally restricted using a horizontal fixed-end anchor with 4000 kN/m/m axial stiffness.

The results of the validation were compared to the measurements presented by Hatami and Bathurst (2005). The results show generally good agreement between the measured and calculated values of the vertical and horizontal toe reactions during all stages of wall construction (see Fig. 1), the horizontal facing displacement (see Fig. 2a), the connection load (see Fig. 2b), and reinforcement strains at the end of construction (see Fig. 3). Details about the modeling, input parameters and comparison between the results can be found in Mirmoradi and Ehrlich (2015a).

3. Parametric study

Parametric studies were carried out with different combinations of wall height, reinforcement stiffness, toe conditions, and facing stiffness. The following three different wall heights, H, were considered: 4 m, 8 m, and 16 m. The length and vertical spacing of the reinforcements were 0.7H and 0.4 m, respectively. The block face was vertical. Fig. 4 shows the geometry of a wall with a height of 4 m. The facing stiffness was evaluated by considering a block facing with a different stiffness modulus defined by Mohamad et al. (2007). The parameter S_i is the relative soil-reinforcement stiffness index, which was developed by Ehrlich and Mitchell (1994) and can be calculated as follows:

$$S_i = \frac{J_r}{kP_aS_v} \tag{1}$$

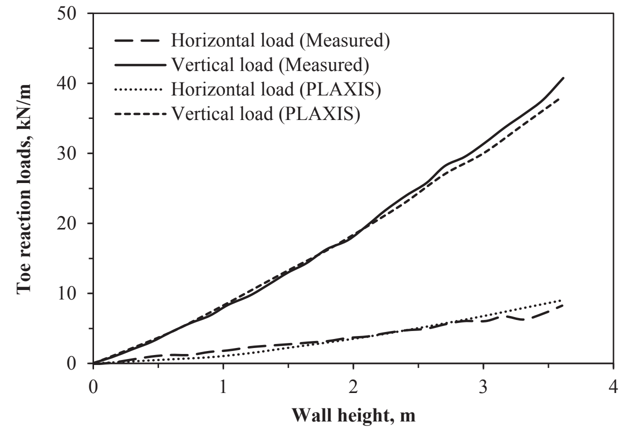

Fig. 1. Comparison of the horizontal and vertical toe reactions determined from numerical analysis and measured from full-scale test (Wall 1, Hatami and Bathurst, 2005).

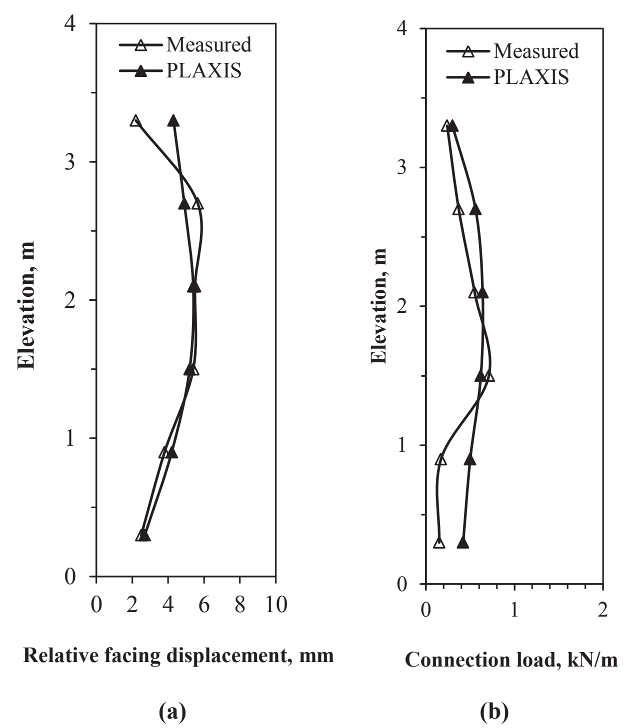

Fig. 2. Comparison of the horizontal facing displacement (a) and connection load (b) determined from numerical analysis and measured from full-scale test (Wall 1, Hatami and Bathurst, 2005).