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INVESTIGATION OF THE PREDICTION CAPABILITY OF THE AASHTO SIMPLIFIED METHOD UNDER WORKING STRESS CONDITIONS

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ABSTRACT

The prediction capability of the AASHTO simplified method is investigated under working stress conditions using the data obtained from experimental and numerical studies. For the experimental evaluation the reinforcement loads measured from three physical models were used. Numerical analyses were carried out to evaluate the combined effects of facing type and stiffness, toe fixity, compaction efforts, and wall height on reinforcement loads. A comparison of the analyses results with the reinforcement requirements determined using the AASHTO method showed that this method may overestimate or underestimate the magnitude of the maximum reinforcement load in reinforced soil walls, depending on the compaction effort, reinforcement stiffness, wall height, facing stiffness, and toe restraint. The results also show that the distribution of the maximum reinforcement load with depth depends substantially on the toe conditions and reinforcement stiffness and it may change from a trapezoidal to triangular shape.

RESUMO

A capacidade de previsão do método simplificado AASHTO é avaliada utilizando estudos experimentais e numéricos, considerando condições de trabalho. Na avaliação experimental, consideraram-se as cargas de reforço medidas em três modelos físicos. As análises numéricas foram efetuadas para verificar os efeitos combinados da rigidez e tipo de faceamento, restrições à movimentação da base do faceamento, os esforços de compactação do aterro e altura do muro nas cargas mobilizadas nos reforços. A comparação dos resultados obtidos utilizando o método da AASHTO indicou que este procedimento pode superestimar ou subestimar a magnitude das cargas máximas nos reforços em muros de solo reforçado, dependendo da energia de compactação, da rigidez dos reforços, da altura do muro, da rigidez do faceamento e das restrições à movimentação da base do faceamento. Os resultados também assinalaram que a distribuição das cargas máximas nos reforços com a profundidade depende substancialmente das restrições à movimentação da base do faceamento e da rigidez dos reforços, e que dependendo das condições vigentes pode variar de uma distribuição triangular para a trapezoidal.

1. INTRODUCTION

Determination of the maximum reinforcement load, T_{max}, is one of the main requirements in the design of reinforced soil walls. The value of T_{max} may be affected by several factors such as wall height, surcharge loading, foundation conditions, facing type and inclination, reinforcement type and stiffness, reinforcement spacing, backfill soil characteristics, backfill soil compaction-induced stress, and toe resistance. In the conventional design methods, e.g., AASHTO simplified method (2014), the influence of some of those factors, such as facing stiffness and toe restraint, are not taken into consideration in the T_{max} calculation.

Reinforcement load predicted by the AASHTO method has been shown to be conservative compared with load measured in several studies (e.g., Allen et al., 2003; Bathurst et al., 2008). Experimental and numerical studies presented by Ehrlich et al. (2012), Mirmoradi and Ehrlich (2014, 2015a,b) showed that the AASHTO method may also under predict the observed values of T_{max}. This discrepancy of the results presented in the above mentioned studies might be attributed to the combined effect of compaction-induced stress, facing stiffness, and toe resistance on the mobilization of T_{max}.

The present paper investigates the predictability of the AASHTO simplified method using the data obtained from experimental and numerical studies. The discrepancy between the results presented in the literature is addressed and discussed with consideration of the results obtained for this study.

2. EXPERIMENTAL STUDY

Instrument data and measurements from three physical model walls constructed at the Geotechnical Laboratory of COPPE/UFRJ are used to evaluate the prediction capability of the AASHTO simplified method under working stress conditions (Saramago 2002; Mirmoradi 2015). These walls are herein identified as Wall 1, Wall 2, and Wall 3. Figure 1 shows front views of Walls 1 and 3. The walls were constructed in a U-shape concrete model box that is 1.5 m high, 3.0 m long, and 2.0 m wide. The vertical spacing of reinforcements and the facing inclination were 0.4 m and 6° to the vertical, respectively.

In Walls 1 and 2 four layers of polyester geogrid were installed at 0, 0.4, 0.8, and 1.2 m above the wall bottom. The reinforcements had a length of 2.12 m, measured from the front of the wall face. The backfill soil of Wall 1 was compacted using a light vibrating plate and a vibratory tamper. For Wall 2, the backfill soil was only compacted by the light compactor (8 kPa). The equivalent static loads of the compactors were determined through Kyowa accelerometers installed in the compactor's body and values of 8 and 63 kPa for light and heavy (tamper) compactors were considered, respectively.

Precast concrete block was used for the face of the walls. The soil unit weight after compaction was 21 kN/m^3. The soil friction angles determined by triaxial and plane strain tests on samples compacted to this unit weight were 42º and 50º, respectively. A 1-m wide zone at the bottom of the walls, including the base of the block facing, was lubricated through a sandwich of rubber sheets and silicon grease in order to allow for movement of the potential failure surface, keeping it away from the wall face. Details about these two walls can be found in Ehrlich et al. (2012) and Ehrlich and Mirmoradi (2013).

In Figure 2 a cross-section of Wall 3 is shown. The height of the wall was 1.2 m. Three layers of reinforcement were installed at 0.2 m, 0.6 m, and 1.0 m above the wall bottom. For the compaction of soil in this wall, the light vibrating plate was used. Similar to Walls 1 and 2, a 1-m wide zone at the bottom of the walls, including below the base of the block face, was lubricated. However, unlike Walls 1 and 2, for Wall 3 lateral movement of the toe was restricted by a steel beam fixed to the concrete U-shape wall box as shown in Figure 1b. At the end of construction of all walls, a vertical surcharge loading of up to 100 kPa was applied to the top of the walls. For Wall 3, after the end of construction and applying the surcharge load, the surcharge load was kept constant on 100 kPa. With the surcharge in place, the toe of Wall 3 was released step by step (0.5 mm horizontal movement allowed in each step). Using this procedure, the toe of the wall was gradually released to the free base condition (Mirmoradi et al. 2016).

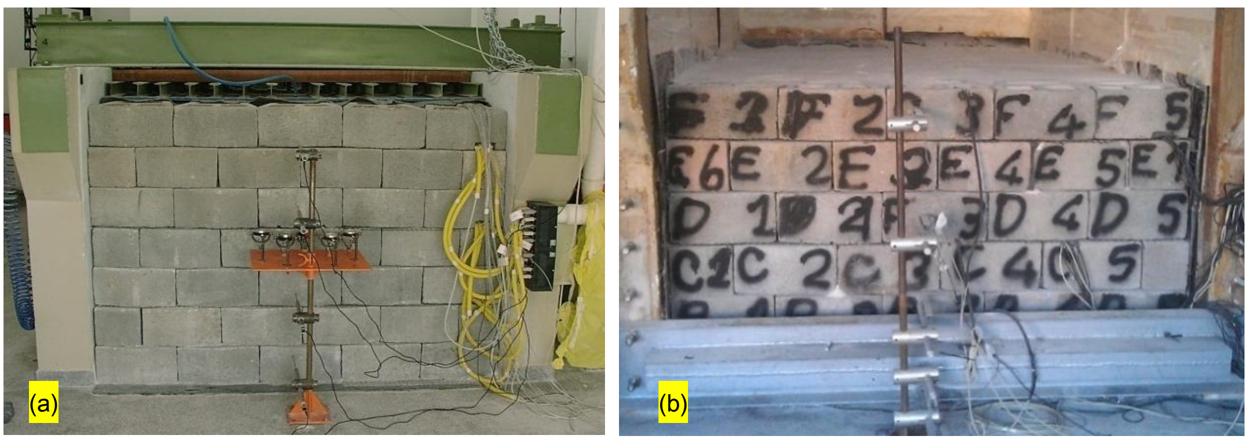

Figure 1. Front Views of Wall 1 (a) and Wall 3 (b)

The reinforcement load values were measured using load cells installed at four points along each reinforcement layer (two load cells in each point) (Figure 2). Two load cells were placed in the active zone and two in the resistant zone. The load cells were attached to the geogrid and measured the mobilized tension along the reinforcements. The load cells allowed tension monitoring without the need to determine the reinforcement stress-strain curves, which are time dependent. The load cells were also capable counterbalancing the temperature effects and the bending moments, and were strong enough to resist the stress induced during the operation of the compaction equipment (Ehrlich et al. 2012; Ehrlich and Mirmoradi 2013; Mirmoradi et al. 2016).

Toe load was measured using the load cells installed on the steel beam fixed to the concrete U-shape wall box. The load cells were placed between the mentioned steel beam and another steel beam installed on the blocks of the first layer. As earlier stated, a 1-m wide zone at the bottom of the walls, including below the block face, was lubricated. Thus, for Wall 3, the toe was free to move laterally and the restriction was guaranteed through the load cells and toe load was measured using those load cells.

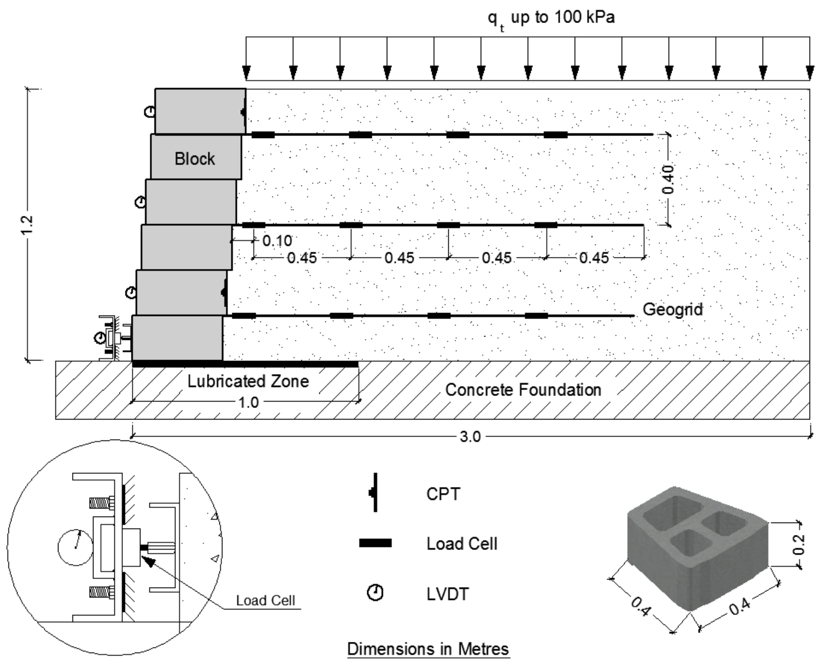

Figure 2. A cross-section view of Wall 3

3. TEST RESULTS

Figure 3 compares the measured values of the summation of the reinforcement loads, $\sum T_{max}$, in Wall 1 (Figure 3a) and Wall 2 (Figure 3b) with the values calculated with the AASHTO simplified method. The equivalent depth, Z_{eq}, corresponds to the value of the external load applied at the top of the wall divided by the soil unit weight (q/γ), added to the real depth of that specific layer. Figure 3a shows that the AASHTO method underestimates $\sum T_{max}$ and this is more pronounced for the lower values of Z_{eq}. Figure 3b indicates, in general, good prediction capability of the AASHTO method for different Z_{eq}

Figure 4 shows a comparison between the values predicted using the AASHTO simplified method and the measured values for Wall 3 during surcharge load application (Figure 4a) and toe release (Figure 4b). This figure illustrates that during surcharge load application, the AASHTO method over-predicts $\sum T_{max}$ and this overestimation increases for higher surcharge loads. During toe release, however, Figure 4b indicates the difference between the measured and calculated values of $\sum T_{max}$ gradually reduces. These figures show the effect of toe restriction and compaction efforts on the prediction capability of the AASHTO design method. The results clearly demonstrate that the AASHTO method may over-predict or under-predict T_{max} depending on toe restraint and backfill soil compaction.

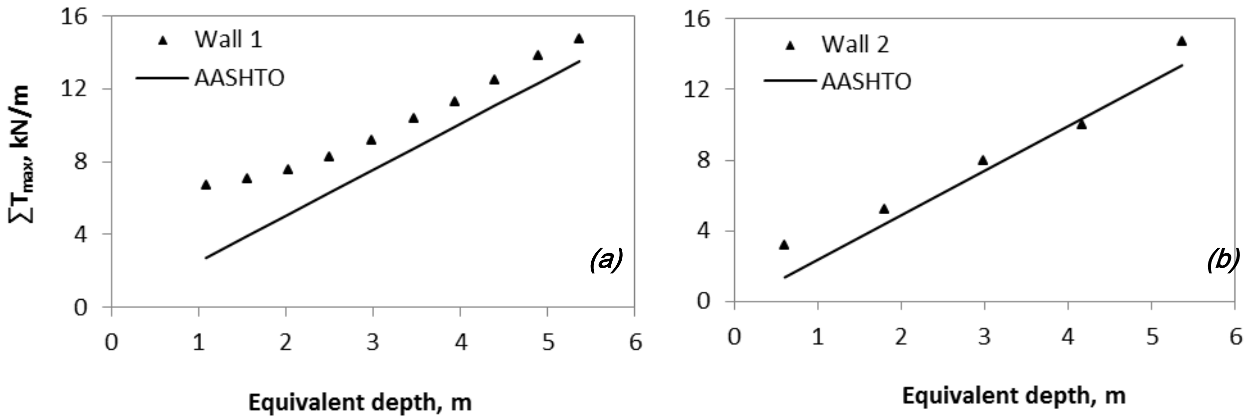

Figure 1. Comparisons of the summation of the reinforcement loads calculated using AASHTO simplified method and measured for Wall 1 (a) and Wall 2 (b).

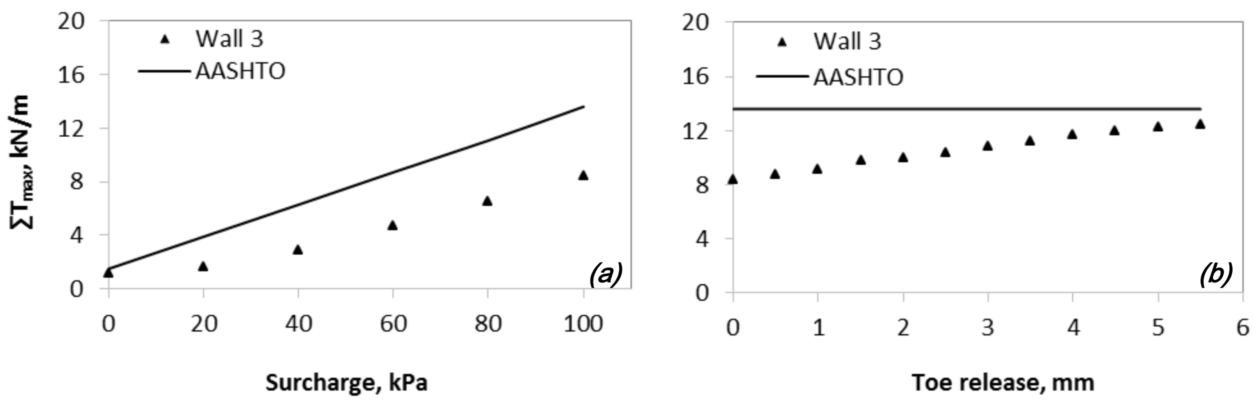

Figure 2. Comparisons of the summation of the reinforcement loads calculated using AASHTO simplified method and measured for Wall 3 during surcharge load application (a) and toe release (b).

4. NUMERICAL STUDY

Numerical modeling was performed for block-face and wrapped-face MSE walls using the 2D finite element program PLAXIS (Brinkgreve & Vermeer, 2002). Data from a full-scale reinforced soil wall built at the Royal Military College of Canada (RMC) was used to validate the numerical modeling for a block-face wall. Results from a physical model constructed at Geotechnical Laboratory of COPPE/UFRJ were used to validate the numerical modeling for the wrapped-face wall. Details about the validation of the models can be found in Ehrlich and Mirmoradi (2013), and Mirmoradi and Ehrlich (2014a, 2015a).

Parametric studies were carried out to evaluate the combined effects of facing type, facing stiffness, toe fixity, compaction efforts, and wall height. Three different wall heights were considered: 4, 8, and 16 m. The length and the vertical spacing of reinforcements were 0.7H and 0.4 m, respectively. Block and wrapped facing with vertical facing inclination was considered. Two different toe fixity conditions were considered (free and fixed base conditions). A hardening soil model was applied. A fixed boundary condition in the horizontal direction was employed on the right lateral border. At the bottom of the model, a fixed boundary condition in both the horizontal and vertical directions was applied.

Reinforcement was modeled as a linear elastic material with perfect interface adherence to the adjacent soil. Three values of the tensile stiffness modulus of reinforcement, Jr, equal to 600 kN/m, 6000 kN/m, and 60000 kN/m were employed. Assuming these values, the relative soil-reinforcement stiffness index, S_i, equal to 0.025, 0.25, and 2.5 are calculated. 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:

$$\mathbf{S_i} = \frac{\mathbf{J_r}}{\mathbf{kP_aS_v}} \qquad [1]$$

where J_r is the tensile stiffness modulus of reinforcement, k is the modulus number (hyperbolic stress-strain curve model), P_a is the atmospheric pressure, and S_v is the vertical reinforcement spacing. The interface parameters defined by Hatami and Bathurst (2005) were used for the block facing. Table 1 lists the input parameters used in the analyses.

Table 1. Input parameters for analysis

Property	Value
Soil parameters	
Model	HS
Peak plane-strain friction angle, ϕ (°)	50
Cohesion, c (kPa)	1
Unit weight, γ (kN/m^3)	20
E_{50}^{ref} (kPa)	42500
E_{oed}^{ref} (kPa)	31800
E_{ur}^{ref} (kPa)	127500
Stress dependence exponent, m	0.5
Failure ratio, R_f	0.9
Poisson's ratio, *υ*	0.2
Reinforcement	
Elastic axial stiffness (kN/m)	600
Modular block parameters	
Model	Linear elastic
Size (m×m)	0.4 ×0.2 (length×height)
Unit weight, γ (kN/m^3)	22
Stiffness modulus (kPa)	1×10^6, 5×10^6, 1×10^7, 5×10^7
Poisson's ratio, *υ*	0.15
Toe condition	Fixed, free

Property	Value
Soil parameters	
Model	HS
Peak plane-strain friction angle, ϕ (°)	50
Cohesion, c (kPa)	1
Unit weight, γ (kN/m^3)	20
E_{50}^{ref} (kPa)	42500
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Elastic axial stiffness (kN/m)	600
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Size (m×m)	0.4 ×0.2 (length×height)
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Stiffness modulus (kPa)	1×10^6, 5×10^6, 1×10^7, 5×10^7
Poisson's ratio, υ	0.15
Toe condition	Fixed, free

5. RESULTS OF THE NUMERICAL STUDY

Figure 5 compares the normalized values of the summation of the maximum load in the reinforcements and the normalized facing stiffness (i.e., $\frac{\sum T_{max}}{\gamma H^2}$ vs. $\frac{EI}{\gamma H^5}$) using the values calculated by PLAXIS and the AASHTO simplified method. The results are for the three different wall heights (4 m, 8 m, and 16 m) and S_i values (0.025, 0.25 and 2.5) for free and fixed base conditions. This figure shows that for the free-base condition and a given S_i value, the results determined using PLAXIS were similar regardless of the normalized facing stiffness. Furthermore, the results corresponding to the Si equal to 0.025 for the walls with free-base condition were relatively accurately represented by the AASHTO simplified method. However, the AASHTO method under-predicts reinforcement loads for S_i equal to 0.25. This value of S_i may be assumed as an upper theoretical limit for the polymeric reinforcement. Thus, just as the lateral earth pressure coefficient for the AASHTO simplified method was modified for walls with steel reinforcement, a similar modification may be required for polymeric reinforcement with high stiffness.

Comparison of the normalized values of the summation of the maximum load in the reinforcements for walls with a fixed-base condition and the values calculated using the AASHTO method indicates the AASHTO method may overestimate the reinforcement loads for walls with higher facing stiffness, as well as lower height and S_i values. For a greater S_i and wall height however, the AASHTO method may underestimate the determined reinforcement loads, even for a block-facing wall with fixed-base conditions. This finding clearly shows that the importance of the toe restraint on the reinforcement load mobilization may be significantly depending on the relative facing stiffness index, $\frac{EI}{\gamma H^5}$, defined by Mirmoradi and Ehrlich (2015a).

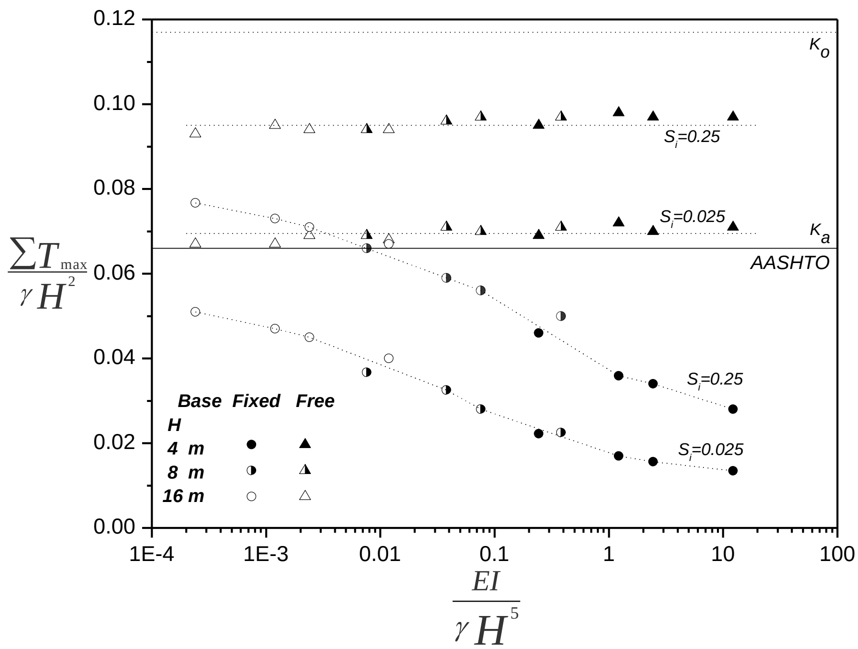

Figure 3. Normalized values of summation of maximum tension in reinforcements versus normalized facing stiffness for different wall height and toe conditions.

Figure 6 presents a comparison of the determined individual values of the maximum reinforcement load, T_{max}, for the wrapped-face wall and block-face wall with fixed and free base conditions with the values calculated using the AASHTO simplified method. Figure 6 presents results for an 8 m high wall with a facing stiffness modulus of 1×10^6 (kPa). This figure indicates similar values calculated using the AASHTO method and the FE analysis for the wrapped-face wall. For the block-face wall however, the ability of the AASHTO method to reasonably accurately predict reinforcement load depends on the toe conditions. For a block-facing wall with free-base condition, the AASHTO method may, in general, reasonably predict the value of reinforcement load, except for T_{max} values in the reinforcement layers at the very bottom of the wall. For the fixed-base condition the AASHTO method over-predicts T_{max} at the lower part of the wall. In the upper part of the wall the AASHTO method appears to reasonably estimate the T_{max} values for both free- and fixed- base toe conditions.

Figure 6 also shows that the distribution of T_{max} with depth is depends on the toe conditions, with the distribution trapezoidal and triangular for the walls with fixed and free-base conditions, respectively. Thus, because the AASHTO design method assumes a triangular distribution of T_{max}, it may overestimate T_{max} in the lower part of the wall where toe restraint may affect the reinforcement load mobilization. Taken together, these findings highlight the significant effect of toe restraint on mobilized tension of reinforcements, especially at the bottom of walls. These results agree with the results presented by Huang et al. (2010) and Leshchinsky and Vahedifard (2012).

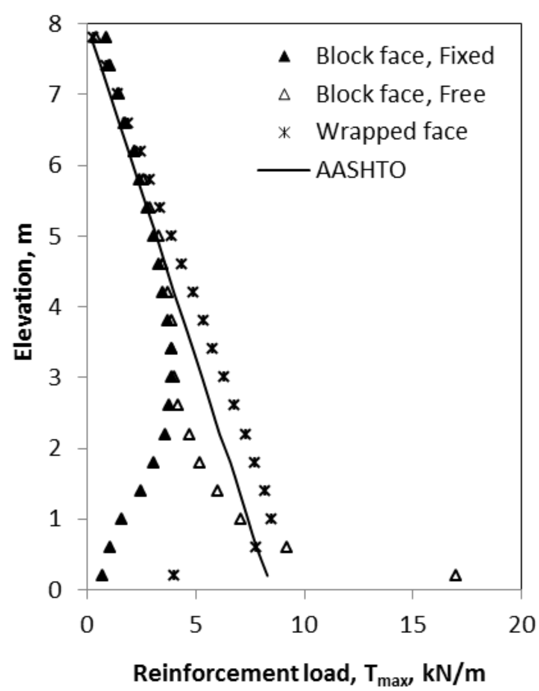

Figure 4. Individual $\mathbf{T_{max}}$ versus depth.

Figure 7 compares T_{max} calculated using the AASHTO method and the values calculated with PLAXIS for an 8-m-high fixed block face wall for three different Si magnitudes. Note that the AASHTO (2014) does not recommend the use of soil friction angle greater than 40° for estimating reinforcement loads in design. For the analyses reported in this paper, where higher soil friction angles were determined from tests, the AASHTO method calculations were performed using soil friction angles of 50° (test results) and 40° (AASHTO limit).

The Tmax values calculated using PLAXIS shows that decreasing the reinforcement stiffness leads to more uniform distribution of the reinforcement load with depth. This agrees with the results presented in previous studies, e.g., Rowe and Ho (1993) and Allen et al. (2004). Figure 7 also indicates that by limiting soil friction angle to 40°, the AASHTO simplified method may over-predict the reinforcement loads for different Si values. The magnitude of over-prediction was more pronounced for low S_i.

On the other hand, when a soil friction angle equal to 50° (representative of the friction angle of soil used in the test walls) is used in the AASHTO analyses, in general, the AASHTO method may reasonably predict the reinforcement loads in the reinforcement layers in the upper part of the wall, in which the combined influence of the facing stiffness and toe resistance do not affect the reinforcement loads. For the lower part of the wall however, the AASHTO method overestimates the maximum reinforcement load, due to the influence of the toe conditions on the reinforcement load mobilization. Note that this over-prediction may significantly decrease for higher reinforcement stiffness values, as the shape of the distribution of T_{max} may change from trapezoidal to triangular.

Figure 8 presents a comparison of T_{max} versus elevation calculated with PLAXIS for a 6.8 m high wrapped-face wall with compaction induced stresses of 63 and 120 kPa, and the AASHTO method. In the numerical modeling, compaction-induced stress was modeled via distribution load at the top and bottom of each backfill soil layer as described by Mirmoradi and Ehrlich (2014a,2015b). The analyses results show that for $Z > Z_c$, the effect of compaction vanishes because the geostatic stress overcomes the induced stress due to backfill soil compaction. Thus, T_{max} is the same; regardless of whether the induced stress due to backfill soil compaction is included ($Z > Z_c$). However, when $Z < Z_c$, T_{max} was found to be greater than the corresponding values for the no compaction condition. Note that the compaction influence depth, Z_c, refers to the equivalent depth below which the overburden stresses exceed the compaction induced stress, and the effects of compaction are no longer felt by the soil. Z_c is given by $\sigma'_{zc,i}$ divided by the soil unit weight, γ. For $\sigma'_{zc,i}$ equal to 63 and 120kPa, the values of Z_c are 3 and 5.7 m, respectively.

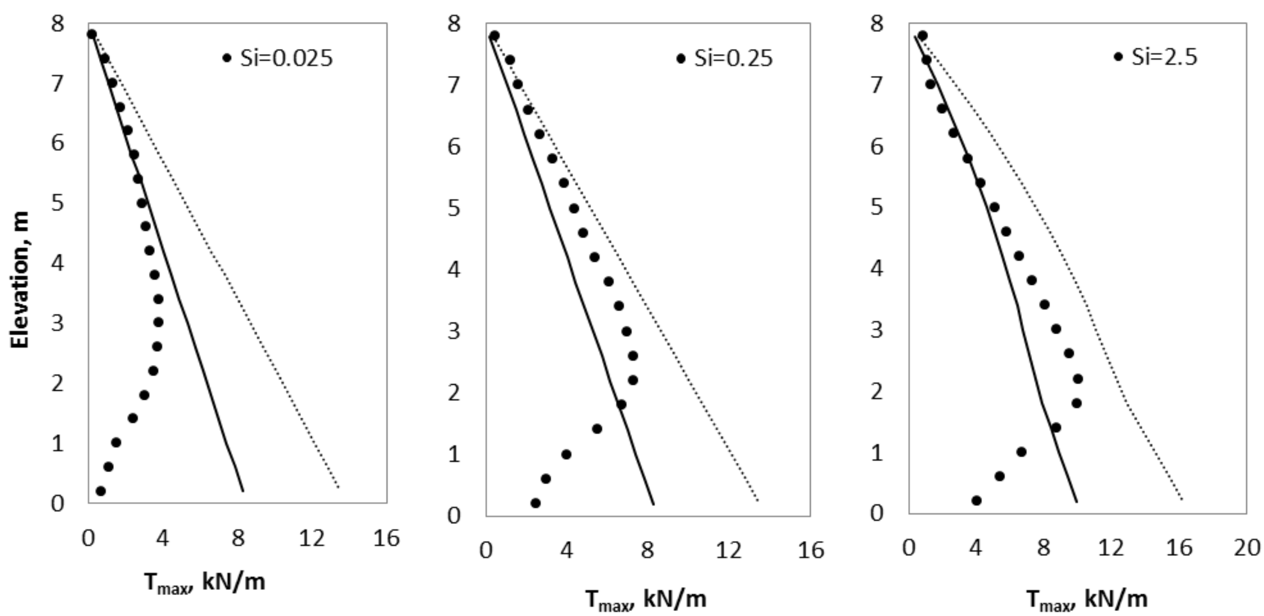

Figure 5. Reinforcement load versus elevation for different reinforcement stiffness. Solid and dotted lines represent the values calculated using AASHTO simplified method for the soil friction angles of 50º and 40º, respectively.

In addition, results show that the AASHTO method properly represents T_{max} values for a no compaction condition. This method however, does not capture the influence of the compaction induced stress in the calculation. Therefore, applying the compaction induced stress results in underestimation of reinforcement loads when reinforcement loads are calculated using this method, for $Z < Z_c$. To overcome this limitation, Mirmoradi and Ehrlich (2015b) proposed a simple analytical procedure that includes the effect of the induced stress due to backfill compaction for use with any conventional design methods of geosynthetic reinforced soil (GRS) walls that do not take into consideration the effect of the compaction-induced stress in their calculations. This approach is based on an equation suggested by Wu and Pham (2010) to calculate the increase in lateral stress in a reinforced soil mass due to compaction. Details about this procedure can be found in Mirmoradi and Ehrlich (2015b).

In Figure 8 for the curves corresponding to the AASHTO modified method, the values of T_{max} determined by the AASHTO simplified method were modified using the mentioned simple analytical procedure to take into consideration the effect of the compaction-induced stress in calculations. Results show a good agreement between the values of T_{max} calculated using PLAXIS and the AASHTO modified method.

6. CONCLUSIONS

The prediction capability of the AASHTO simplified method was investigated under working stress conditions using data obtained from experimental and numerical studies. The experimental evaluation used the values of the reinforcement loads measured from three physical models constructed at the Geotechnical Laboratory of COPPE/UFRJ. Numerical analyses were carried out using PLAXIS 2D to evaluate the combined effects of facing type, facing stiffness, toe fixity, compaction efforts, and wall height. The main findings of this study are summarized, as follows:

A comparison of the results with the AASHTO method showed that the accuracy of reinforcement loads predicted using this method depends on the compaction effort, reinforcement stiffness, wall height, facing stiffness, and toe restraint. The results indicate that for a wrapped-face wall, the AASTHO method may properly represent the values of the maximum reinforcement load, T_{max}, in which no compaction-induced stress was assumed. However, the AASTHO method may underestimate T_{max} for the walls in which a high compaction-induced stress assumed.

The results corresponding to an S_i equal to 0.025 for the walls with free-base condition were reasonably well predicted by the AASHTO simplified method, but the AASHTO method under-predicts reinforcement loads for S_i equal to 0.25. An S_i value of 0.25 may be assumed as an upper theoretical limit for the polymeric reinforcement. Thus, just as the lateral earth pressure coefficient for the AASHTO simplified method was modified for the walls with steel reinforcement, a similar modification may be warranted for high stiffness polymeric reinforcement.

The AASHTO method over-predicts T_{max} for walls with fixed-base conditions. This is more pronounced for walls with higher facing stiffness, as well as those of lower height and reinforcement stiffness values. For greater reinforcement stiffness and wall height, the AASHTO method may underestimate the reinforcement load values, even for a block-facing wall with fixed-base conditions. This finding clearly shows the importance of the toe restraint on the reinforcement load mobilization and how reinforcement load may vary considerably depending on the relative facing stiffness index, $\frac{EI}{\gamma H^5}$ as defined by Mirmoradi and Ehrlich (2015a).

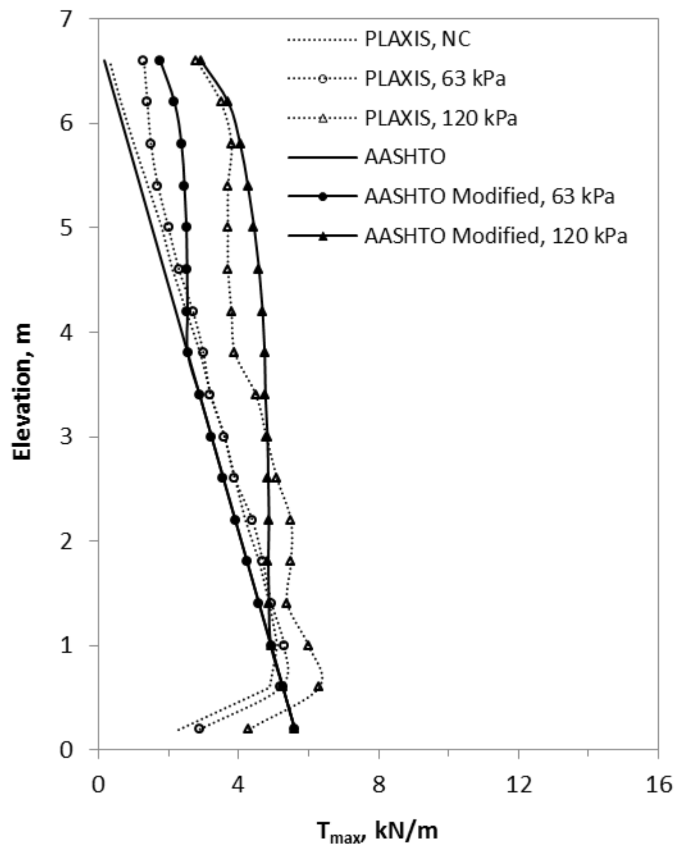

Figure 6. Individual T_{max} versus depth

The results also show that the distribution of T_{max} with depth depends substantially on the toe conditions and reinforcement stiffness and it may change from a trapezoidal to triangular shape. The AASHTO design method assumes a triangular shape of the distribution of T_{max} with depth. However, the analyses results show the accuracy of the calculated T_{max} using this method may be significantly affected by the toe conditions and reinforcement stiffness values.

ACKNOWLEDGEMENTS

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