Numerical Evaluation of the Behavior of Reinforced Soil Retaining Walls

Simulation numérique du comportement de murs de soutènement en sol renforcé

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ABSTRACT: In this article, the behavior of reinforced soil walls was studied by performing a numerical analysis using the finite element method. The numerical approach was validated with the results of a wrapped-faced full-scale reinforced soil wall. In addition, parametric studies were carried out with different combinations of: facing type, reinforcement stiffness, compaction efforts, and shear resistance parameters of the backfill soil. Results indicated that for depths below which the vertical induced compaction stresses are less than the overburden stress, the maximum tension in the reinforcements is the same, irrespective of the values of compaction effort. However, for lower depths, the tension in the reinforcements increased with the induced compaction stress. In addition, for the block facing wall, the maximum tension in the reinforcement occurred near the mid-height of the wall. However, for the wrapped faced wall, the maximum values occurred close to the bottom of the wall. An increase of reinforcement stiffness led to greater values of tension in the reinforcement for both wrapped and block faced walls. Moreover, an increase of backfill soil shear resistance led to lower values of tension in the reinforcements.

RÉSUMÉ : Dans cet article, le comportement des murs en terre armée a été étudié en effectuant une analyse numérique utilisant la méthode des éléments finis. L'approche numérique a été effectuée en se basant sur les résultats d'un mur en terre armée à l'échelle réelle avec un parement enrobé d'une nappe géosynthétique. De plus, des études paramétriques ont été réalisées avec différentes combinaisons de type de parement, de rigidité d'armature, d'efforts de compactage et de paramètres de résistance au cisaillement du remblai. Les résultats ont indiqué que, pour des profondeurs au-dessous desquelles la contrainte verticale de compactage était inférieure à la contrainte de surcharge, la tension maximale dans l'armature était la même, quelles que soient les valeurs de l'effort de compactage. Toutefois, pour des profondeurs inférieures, la tension dans l'armature augmentait avec la contrainte de compaction. De plus, pour le parement mural en bloc, la tension maximale dans l'armature s'est produite à environ mi-hauteur du mur. Cependant, pour le parement mural enrobé par une nappe géosynthétique, les valeurs maximales se sont produites près du pied du mur. Une augmentation de la rigidité de l'armature a conduit à de plus grandes valeurs de tension dans l'armature, aussi bien pour le parement mural en bloc que pour le parement mural enrobé par une nappe géosynthétique. En outre, l'augmentation de la résistance au cisaillement du remblai a entraîné une baisse des valeurs de tension dans l'armature.

KEYWORDS: Numerical modeling ; Reinforced soil ;Walls ; Compaction effort ; Facing stiffness ; Reinforcement stiffness ;

1 INTRODUCTION

The behavior of reinforced soil was evaluated using finite element method in the middle 70s (e.g., Romstad et al., 1976). In recent decades, several numerical analyze using the codes of the finite element method or finite difference method have been performed to consider the different geometry and parameters of GRS walls. Examples are reported by Ling and Leshchinsky (2003), Hatami and Bathurst (2006), and Guler et al. (2007), among others.

The purpose of the present study is the numerical evaluation of the behavior of reinforced soil retaining walls using the finite element method. The numerical analysis was carried out using the PLAXIS 2D computer program. The modeling was validated with the results of a full-scale reinforced soil wall experiment performed at the Geotechnical Laboratory of COPPE/UFRJ. Parametric studies were carried out with different combinations of: facing type, reinforcement stiffness, compaction efforts, and shear resistance parameters of the backfill soil.

2 MODEL VALIDATION

The finite element program PLAXIS (Brinkgreve and Vermeer, 2002) was used for the numerical evaluation of the compaction effect on the behavior of reinforced soil walls. Full-scale reinforced soil wall modeling, performed at the Geotechnical Laboratory of COPPE/UFRJ, was used for validation of the performed analyzes.

The physical model used in this study simulated the behavior of a 6.8 m high wrapped faced wall (considering the surcharge load values up to 100 kPa) representing a portion of the prototype (see Fig. 1). The model wall was 1.4 m high with a facing inclination of 6° to the vertical. The length and the vertical spacing of the geogrid were 2.12 m and 0.4 m, respectively. The value of axial reinforcement stiffness was equal to 600 kN/m. The model wall was constructed in seven soil layers, each 0.2 m thick. Layers were compacted by using both a light vibrating plate (Dynapac LF 81) and a vibratory tamper (Dynapac LC 71-ET). Equivalent vertical induced stresses due to soil compaction of 8.0 kPa for the vibrating plate and 63 kPa for the vibratory tamper were determined. The soil unit weight after compaction was 21 kN/m^3. The soil friction angles, determined by triaxial and plane strain tests, were 42° and 50°, respectively. Tensions were monitored in the reinforcements numbered 2, 3, and 4 (see Fig. 1). Load cells were installed at four points along the reinforcement. The reader is directed to the paper by Ehrlich et al. (2012) for additional information about the construction process, the evaluation of the induced vertical stress due to soil compaction, and the instrumentation for the performed physical modeling.

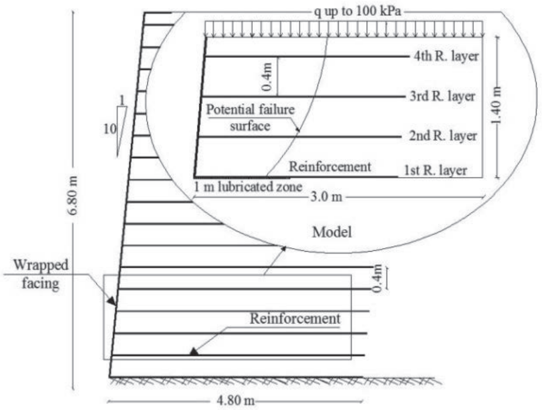

Figure 1. View of prototype and model.

Fig. 2 shows the geometry of the numerical model used in the performed analyzes. Note that the simulated geometry represented the prototype. To compare the values determined with PLAXIS and the measured ones, the summations of the mobilized maximum tension in the reinforcements “a”, “b”, and “c” (see Fig. 2), which were representative of the verified values in the 2nd, 3rd, and 4th reinforcement layers in the physical model, were used (see Fig. 1). The wall was 6.8 m high and the length of soil mass assumed in the performed analysis was 11 m. The length and the vertical spacing of reinforcements were 4.8 m and 0.4 m, respectively. The wrapped facing with an inclination of 6° to the vertical was modeled. In the performed study, the hardening soil model was applied, which is a hyperbolic soil model, very similar to the model of Duncan and Chang (1970). Boundary conditions of the performed numerical modeling consider horizontal restriction for the right side, and horizontal and vertical restrictions for the bottom of the wall. Stage construction was considered; for every 0.2 m of soil placed, the layer was compacted, until the final wall height was reached. Compaction was simulated by applying a single load-unload stress cycle of 63 kPa distribution load at the top and bottom of each backfill soil layer. This simple approach might represent the actual multi-cycle load-unload stress path during compaction (Ehrlich and Mitchell, 1994).Table 1 shows the input parameters used in this validation. The backfill soil stiffness and resistance parameters were determined from plane-strain tests.

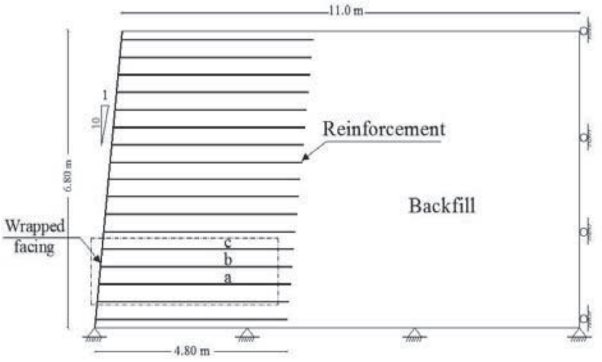

Figure 2. Model geometry adopted from prototype.

Table 1. Input parameters for validation analysis.

Parameter	Value
Backfill Soil	
Peak plane strain friction angle ϕ (°)	50
Cohesion c (kPa)	1.0
Dilation angle Ψ (°)	0.0
Unit weight γ (kN/m^3)	21
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	0.7
Poisson’s ratio υ	0.25
Reinforcement	
Elastic axial stiffness (kN/m)	600
Face	
Elastic axial stiffness (kN/m)	60
Elastic bending stiffness (kNm^2/m)	1.0

In Fig. 3, the FEM results are evaluated. This figure shows the comparison of the determined summation of the maximum reinforcement tensile stress, T_{max}, with those observed from the physical modeling study, and also the values predicted by the Ehrlich and Mitchell (1994) method. For details about the prediction of T_{max} by this method, the reader is directed to the papers by Ehrlich and Mitchell (1994) and Ehrlich et al. (2012). The equivalent depth of the soil layer (Z_{eq}) is defined by:

$$Z_{eq} = Z + q/\gamma \tag{1}$$

where Z, q, and γ are the real depth of the specific layer, surcharge load value, and soil unit weight, respectively. As shown, the values measured from the physical model were properly represented by both the analytical method (Ehrlich and Mitchell, 1994) and the numerical (PLAXIS) method. However, for the values of equivalent depth lower than the compaction influence depth, i.e., $Z_{eq} < 3$ m, the results of the numerical simulation using PLAXIS was more accurate than the Ehrlich and Mitchell (1994) method (maximum difference less than 6%). When surcharge load values increased, (i.e., $Z_{eq} > 3$ m), the measurements, and the values predicted by the Ehrlich and Mitchell (1994) method and PLAXIS, fully agreed.

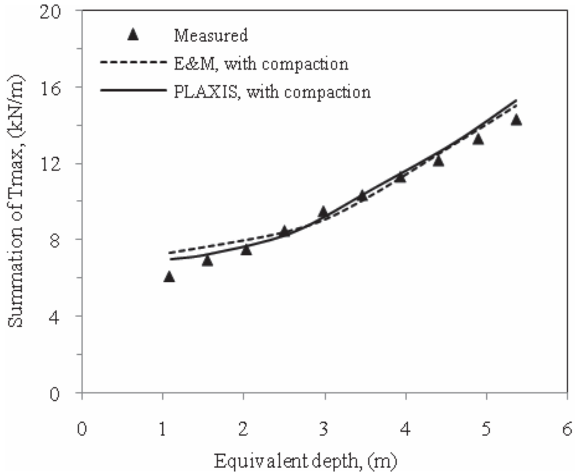

Figure 3.Comparison of predicted and measured summations of maximum tensions along the 2nd, 3rd, and 4th reinforcement layers.

3 PARAMETRIC STUDY

Parametric studies were carried out with different combinations of facing type, reinforcement stiffness, compaction efforts, and shear resistance parameter of the backfill soil. In these analyzes the same geometry of the validation model was considered. Facing type was evaluated considering block and wrapped facing wall. No compaction condition and compaction effort equal to 120 kPa were considered in addition to the 63 kPa compaction effort used for model validation. The modular blocks were simulated as linear elastic units. The interface property defined by Hatami and Bathurst (2006) was used to simulate the block-block interface. Table 2 presents the value of the parameters used in the performed analyzes. Note that S_i is the relative soil-reinforcement stiffness index (Ehrlich and Mitchell, 1994), calculated by

$$S_i = J_r/kP_aS_v \qquad (2)$$

where J_r is the tensile stiffness modulus of reinforcement, S_v is the vertical reinforcement spacing, P_a is the atmospheric pressure and k is the modulus number (hyperbolic stress-strain curve model).

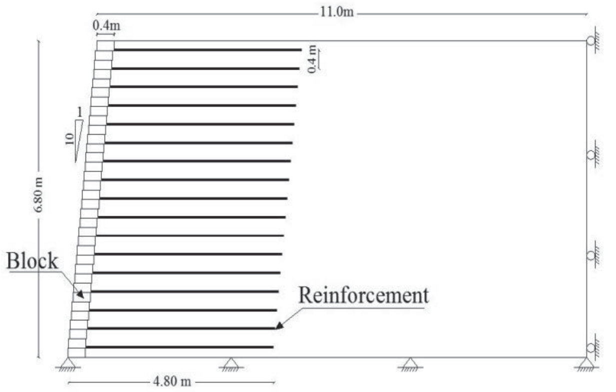

Figure 4. Model geometry used in parametric study.

Table 2. Input parameters used for parametric study.

Parameter	Value
Modular block properties	
Model	Linear elastic
Size, (m × m)	0.4 × 0.2 (length × height)
Unit weight γ (kN/m^3)	21.8
Poisson´s ratio υ	0.15
Stiffness modulus (kPa)	1 × 10^6
Block-block interface	
Friction angle (°)	57
Cohesion (kPa)	46
Soil-reinforcement stiffness index S_i	0.01, 0.025, 0.1, 0.25, 1
Backfill soil	
friction angle ϕ (°)	20, 35, 50
Cohesion c (kPa)	1, 10
Compaction effort (kPa)	0, 63, 120

4 RESULTS

Fig. 5 shows the values of T_{max} versus depth for different compaction efforts (i.e., no compaction, 63 kPa, and 120 kPa) for block (dotted line) and wrapped (solid line) faced walls. In performed analyses reinforcement stiffness index, S_i, equal to 0.025 was assumed. Comparison of the curves related to the results considering or not considering the induced stress due to compaction shows a very consistent representation of the expected behavior for block and wrapped faced walls. For a depth greater than the compaction influence depth, i.e., $Z > Z_c$, the effect of compaction vanishes because the geostatic stress overcomes the induced stress due to the backfill soil compaction and T_{max} for the analyzes considering or not considering the induced stress due to backfill soil compaction would be the same. Z_c is given by $\sigma'_{zc,i}$ divided by the soil unit weight ($\sigma'_{zc,i}/\gamma$). However, for depths lower than the compaction influence depth ($Z < Z_c$), T_{max} would be greater than the corresponding values for the condition of no compaction. This behavior is verified in both models with different facing types. These results agree with the reported physical modeling results by Ehrlich et al. (2012), which evaluated the effect of compaction on the behavior of GRS walls.

In addition, Fig. 5 indicates that for the block faced wall, the maximum tension in the reinforcement occurred almost in the reinforcements placed at the mid-wall height. However, for the wrapped faced wall, the maximum value occurred at a lower level (close to the bottom of the wall). The difference in this behavior might be attributed to the combined effect of facing stiffness and toe resistance, which is different in these two types of wall.

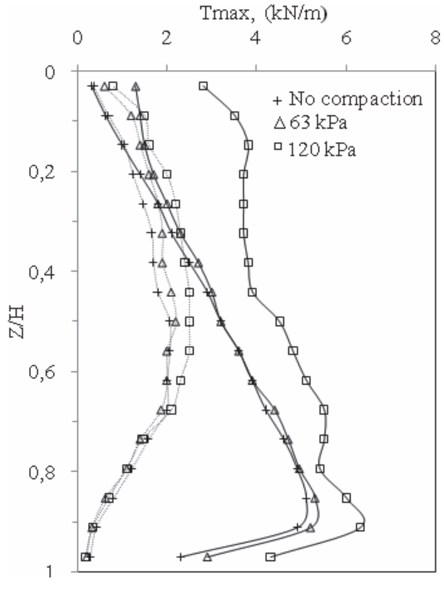

Figure 5.Values of T_{max} versus depth for different compaction efforts. Solid and dotted lines represent wrapped and block faced walls, respectively.

Fig. 6 presents the values of the summation of T_{max} versus different reinforcement stiffness for block and wrapped faced wall. In this figure, the solid and dashed lines represent results related to the backfill soil modeled with cohesion values equal to 1 kPa and 10 kPa, respectively.

Fig. 6 shows that for both facing types, the value of summation of maximum tension in the reinforcement, $\sum T_{max}$, increases with reinforcement stiffness. For the wrapped faced wall, the rate of increase of $\sum T_{max}$ for the lower reinforcement stiffness is less compared with the verified ones for the higher values of S_i. However, for the block faced wall, this rate is almost constant, irrespective of the reinforcement stiffness values. Furthermore, comparison of the curves related to different cohesions, i.e., 1 kPa and 10 kPa, displays that lower cohesion led to a greater value of $\sum T_{max}$, irrespective of facing type. For the wrapped face wall, the difference between the determined values of $\sum T_{max}$ was greater for lower values of S_i, where the cohesion of the backfill soil was assumed equal to 1 kPa and 10 kPa. Note that the difference in the determined results decreased with an increase of S_i. However, for block facing the inverse behavior was verified. This discrepancy might be related to toe resistance and lateral movement restriction verified in the block faced wall, compared with the mobilized one in the wrapped faced wall.

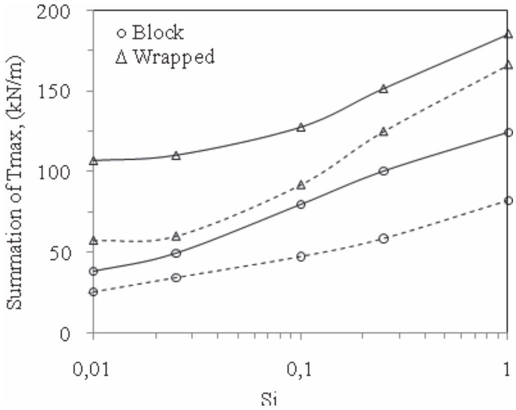

Figure 6.Values of the summation of T_{max} versus reinforcement stiffness for no compaction condition and different facing types. Solid line: cohesion equal to 1 kPa, dashed line: cohesion equal to 10 kPa.

Fig. 7 indicates the values of the summation of T_{max} versus friction angle of the backfill soil, determined in the performed analyzes considering block and wrapped faced walls. In this figure, the solid and dashed lines represent results related to the wall in which the backfill soil is modeled with cohesion values equal to 1 kPa and 10 kPa, respectively. As shown for both the block and wrapped faced walls, $\sum T_{max}$ declines with an increase of the backfill soil friction angle. However, the rate of decrease for the wrapped faced wall is greater than that of the block faced wall, and this behavior was clearer for the wall where the backfill soil was modeled with a cohesion value equal to 10 kPa. Fig. 7 also shows that for the wall where the backfill soil was modeled with a greater friction angle, $\sum T_{max}$ is less affected by the magnitude of the backfill soil cohesion. This behavior can be clearly seen for the block faced wall.

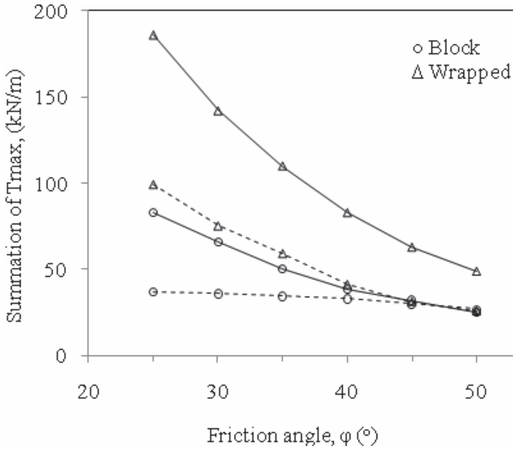

Figure 7. Values of the summation of T_{max} versus friction angle of the backfill soil for no compaction condition and different facing types. Solid line: cohesion equal to 1 kPa, dashed line: cohesion equal to 10 kPa.

5 CONCLUSIONS

In this paper, the behavior of reinforced soil walls was studied through numerical analyzes carried out using the finite element method. The numerical analysis was performed using the PLAXIS 2D computer code. The modeling was verified with the results of a full-scale reinforced soil wall experiment performed at the Geotechnical Laboratory of COPPE/UFRJ. Comparison of measured maximum reinforcement tensile stress and values predicted by both PLAXIS and the Ehrlich and Mitchell (1994) method show good agreement. In addition, parametric studies were carried out with different combinations of: facing type, reinforcement stiffness, compaction efforts, and shear resistance parameters of the backfill soil. Analysis of the results showed that:

Comparison of the results for different values of compaction effort shows that for depths greater than the compaction influence depth, i.e., $Z > Z_c$, the effect of compaction vanishes because the geostatic stress overcomes the induced stress due to backfill soil compaction and the maximum tension in the reinforcement, T_{max}, for the analyzes considering or not considering the induced stress due to backfill soil compaction would be the same. However when $Z < Z_c$, T_{max} would be greater than the corresponding values for the condition of no compaction.

The summation of the maximum tension in the reinforcement $\sum T_{max}$, increases with reinforcement stiffness. For the wrapped faced wall, the rate of increase of $\sum T_{max}$ for the lower reinforcement stiffness is less compared with the higher ones. However, for the block faced wall, this rate is almost constant, irrespective of the reinforcement stiffness value. $\sum T_{max}$ for the walls modeled with greater backfill soil cohesion is less than that for those with lower backfill soil cohesion, irrespective of facing type. For block faced wall, for analyzes where the cohesion of backfill soil was assumed equal to 1 kPa and 10 kPa, the difference between $\sum T_{max}$ for lower reinforcement stiffness values was less compared with higher reinforcement stiffness. However, for the wrapped faced wall, the inverse behavior was verified.

An increase of backfill soil friction angle leads to lower values of $\sum T_{max}$. However, the rate of decrease for the wrapped faced wall is greater than that for the block faced wall. Furthermore, for walls in which the backfill soil was modeled with greater friction angle, $\sum T_{max}$ is less affected by the magnitude of the backfill soil cohesion.

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