INFLUENCE OF FACING PANEL RIGIDITY ON PERFORMANCE OF REINFORCED SOIL RETAINING WALLS: A NUMERICAL STUDY

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Abstract: Geosynthetic-reinforced soil retaining walls are typically designed on considerations of limit equilibrium. These methods disregard the effects due to foundation condition, reinforcement stiffness, facing type and other factors. Deformations of the wall are generally not explicitly considered in design.

In this work, the two-dimensional finite difference Fast Lagrangian Analysis of Continua (FLAC) program was used to carry out parametric analyses. The numerical study was carried out to analyse the influence of facing panel rigidity and wall height on horizontal deformations and reinforcement tensile loads of geosynthetic reinforced soil retaining walls with continuous facing panel.

For the same facing panel bending stiffness different values of wall height are investigated. The numerical analyses showed that the pattern of normalized horizontal displacements and normalized reinforcement tensile loads, for structures with the same facing panel rigidity and reinforcement stiffness factor, are distinct. However, if the facing panel bending stiffness for distinct wall heights obeys to a presented equation, good agreements related to normalized displacements and normalized reinforcement loads are achieved.

Keywords: reinforced soil wall, retaining wall, numerical, rigid facing, bending characteristic.

INTRODUCTION

A numerical study was carried out to clarify the influence of facing panel rigidity on horizontal displacements and reinforcement tensile loads of geosynthetic reinforced soil retaining walls with continuous facing panel. The two-dimensional finite difference Fast Lagrangian Analysis of Continua (FLAC) program was used. A preliminary analysis was performed to confirm that FLAC gives similar results to those reported in the literature using finite elements methods.

COMPARISON OF FLAC WITH FEM RESULTS

General

A preliminary comparison was made to ensure that FLAC gives similar results to those reported in the bibliography using finite elements methods (FEM). This comparison was carried out with results of a numerical study of reinforced soil walls, with a continuous panel facing, reported by Rowe & Ho (1998). This numerical example was chosen among others relating to experimental studies, because it presents a good material characterization and construction sequence.

Bathurst & Hatami (1998) had also presented a comparison between FLAC numerical results and results reported by Rowe & Ho (1997). However the present work and the study presented by these authors have some differences. Rowe & Ho (1998) carried out a plane strain finite analysis using a finite element program (AFENA), which was modified by the authors to allow for modelling of reinforced soil walls. The continuous panel wall is 6.0 m high, reinforced with six horizontal reinforcement layers of 4.25 m long. Table 1 presents geometric, reinforcement and soil properties of this numerical example.

Table 1. Parameters of the example presented by Rowe & Ho (1998)

Parameter	Symbol	Value
Wall height (m)	H	6
Reinforcement length (m)	L	4.25
Vertical spacing of reinforcement (m)	S_v	1
Stiffness of reinforcement (kN/m)	J	2000
Soil Young's modulus (kN/m^2)	E_s	50000
Soil Poisson's ratio	ν	0.3
Wall bending stiffness (kNm^2)	EI	5500
Soil friction angle (º)	ϕ	35
Soil-reinforcement friction angle (º)	δ_R	35
Soil-to-face friction angle (º)	δ	20
Soil dilatancy (º)	ψ	6

The fill was modelled as an elasto-plastic material, with a Mohr-Coulomb yield criterion and a non-associated flow rule. The wall facing was assumed as an elastic material and the foundation of the structure was supposed rigid. The wall was constructed in 24 layers and it was assumed that the wall facing, hinged at its base, was fully supported in the horizontal direction during construction. The panel supports were released in sequence from the top of the structure.

The reinforcement layers were modelled using linear elasto-plastic cable elements, with negligible compressive strength. The interface between the reinforcement and the soil was modelled by a grout material (Itasca 2002) with an interface friction angle of 35º (see Table 1) and a bond stiffness of 2×10^3 kN/m/m. The soil-to-face interface was modelled using interface elements and the soil-to-face friction angle was taken equal to 20º (see Table 1).

Comparison of results

Figure 1 shows the lateral displacements at the wall face and behind the reinforced soil block achieved by FLAC and reported by Rowe & Ho (1998). As illustrated in this figure, the displacement profiles are in close agreement.

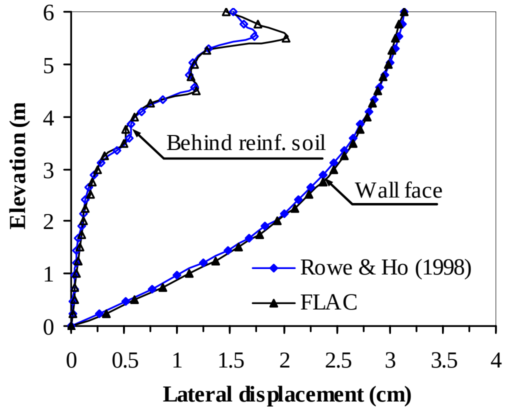

Figure 1. Lateral displacements. Comparison of FEM reported by Rowe & Ho (1998) and FLAC results

Figure 2a illustrates the maximum axial force reached in each reinforcement layer. The results are in close agreement too, although the loads obtained by FLAC are lower than FEM results. The greatest difference occurs in the lower reinforcement layer. As shown in Figure 2b, the strains along this reinforcement layer are slightly different, particularly close to the wall connection. The differences may be due to the way the reinforcement layers were modelled.

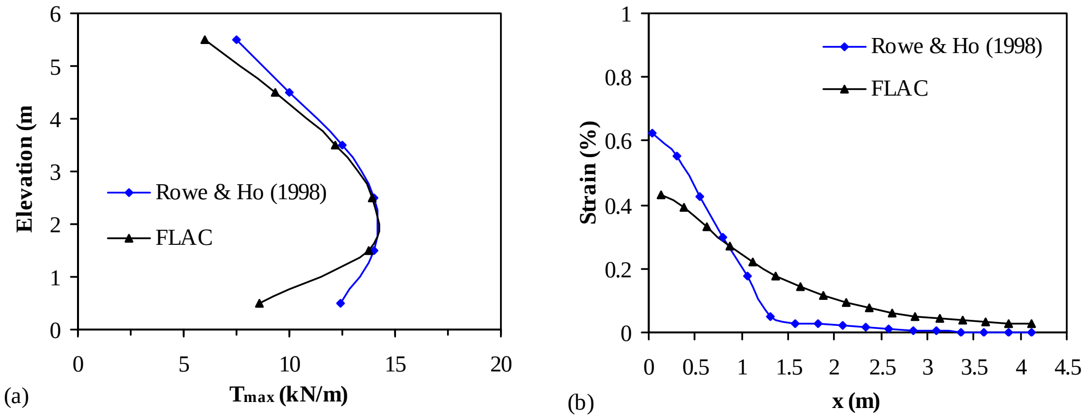

Figure 2. Comparison of FLAC and FEM results: a) maximum axial force in reinforcement; b) strain along the lower reinforcement layer

NUMERICAL ANALYSES

General

The main objective of this study was the analysis of the influence on the lateral displacements and reinforcement loads of reinforced soil retaining walls, with continuous panel, of some design parameters, namely, the facing panel rigidity and the wall height. The study regards a reinforced wall of height H = 6m with 10 horizontal reinforcement layers, uniformly spaced, of length L = 4.2 m, attached to a continuous facing. The wall and soil regions were supported by a stiff foundation.

The reinforcement length, L, was selected to give L/H = 0.7, where H is the height of the structure. This ratio value of L/H is the minimum recommended by FHWA (2001) for static design. The numerical grid for the reference case is illustrated in Figure 3. The width of the backfill was extended to 35 m beyond the back of the facing panel to represent an infinitely wide region.

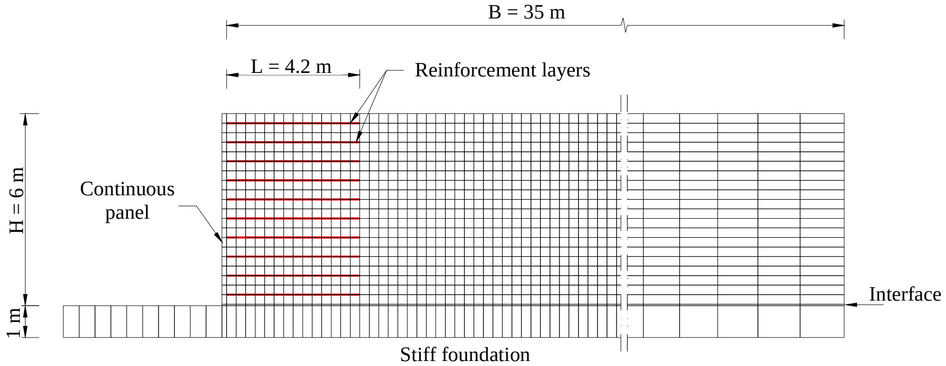

Figure 3. Numerical grid for the reference case

The fill was modelled as a purely frictional elasto-plastic material, with a Mohr-Coulomb yield function and a non-associated flow rule. The friction angle of the soil was $\phi = 35^{o}$ and the unit weight $\gamma = 22$ kN/m^3. The bulk and shear modulus values of the soil were K = 50.0 MPa and G = 23.1 MPa, respectively. The wall facing was assumed as an elastic material. For the reference case it was assumed a facing panel with thickness equal to 0.15 m, 0.237 GPa and 0.2 for the Young modulus and Poisson ratio, respectively.

The reinforcement layers were modelled using linear elasto-plastic cable elements with negligible compressive strength. The interface between the reinforcement and the soil was modelled by a grout material with an interface friction angle of 30º and a bond stiffness of 5×10^6 kN/m/m. The linear elastic stiffness value for the reinforcement was taken equal to 1000 kN/m.

The facing panel-reinforced soil interface was modelled using interface elements, with a friction angle of 20º, normal stiffness and shear stiffness equal to 2×10^6 kPa/m. The facing panel was seated on a thin layer of soil with friction angle equal to 20º and remaining parameters having the same values of backfill soil properties. The wall is free to slide horizontally and rotate about the toe. For the reference case it was assumed that the reinforced soil retaining wall was incrementally constructed, that means that the support is only provided to each lift of soil as it is placed.

Influence of facing panel properties

Effect of facing panel bending stiffness

The facing of reinforced soil retaining walls could be materialized with a large variety of materials. Since a wrapped facing until a full-height concrete panel or concrete modular block systems. To this diversity of facing systems is associated, obviously, a wide range of values of facing rigidity.

To evaluate the effect of facing panel bending stiffness on the behaviour of geosynthetic reinforced soil retaining walls, with continuous facing panel some numerical analyses were carried out. In order to isolate the effect of facing bending stiffness (EI), all the analyses were performed considering a facing panel with thickness equal to 0.15 m. Four values of EI were considered: 11.0 kNm^2, 66.7 kNm^2 (reference case), 421.9 kNm^2 and 2812.5 kNm^2. These values were achieved with elastic modulus of 0.039 GPa, 0.237 GPa, 1.5 GPa and 10 GPa, respectively. The influence of facing panel rigidity on the horizontal displacements at the end of construction is illustrated on the Figure 4. The horizontal displacements (δ_h) appear normalized by the wall height (H).

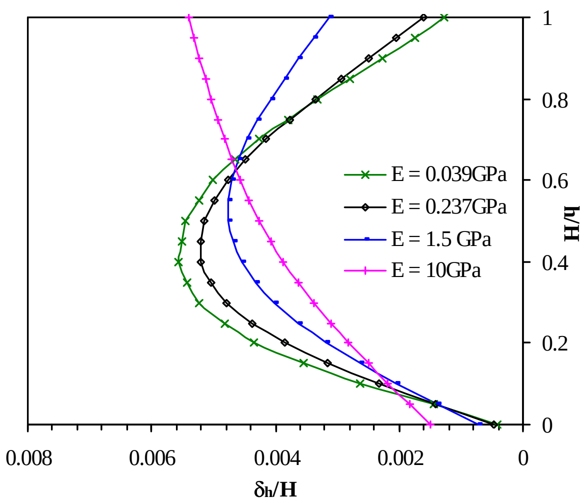

Figure 4. Effect of facing panel bending stiffness on normalized horizontal displacements

It can be observed from Figure 4 that wall bending stiffness has a great influence on the pattern of lateral displacements. When the facing panel rigidity increases the location of maximum horizontal displacement rises on wall height. However, the differences on its values are not very expressive. The maximum horizontal displacement reaches 0.56% and 0.54% of the wall height, for the most flexible facing panel and for the rigid panel, respectively. Nevertheless, if the facing panel bending stiffness increases from 11.0 kNm^2 to 421.9 kNm^2, the maximum displacement will decrease from 0.56% to 0.48% of H (decrease of 14% on maximum displacement for an increase of 38 times on EI).

Numerical analyses performed by Rowe & Ho (1998) showed that increasing a hundredfold the wall bending stiffness, the maximum horizontal displacement of the facing decreases 15%. Figure 5 shows the maximum reinforcement tensile loads, mobilized along the reinforcement length, for distinct values of facing rigidity. The reinforcement loads appear normalized by $K_a \gamma H S_v$ where, K_a is the active earth pressure coefficient, γ is the unit weight of the soil, H is the wall height and S_v is the vertical spacing between reinforcement layers.

Except the lower reinforcement layer, where the tensile load decreases due to the foundation constraint, when the facing panel is more flexible the maximum reinforcement loads tend to increase with depth. Increasing the wall bending stiffness, reinforcement load distribution becomes more uniform.

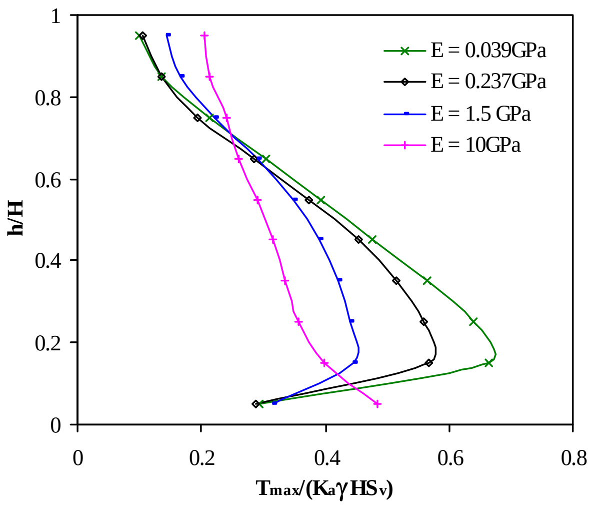

Figure 5. Effect of facing panel bending stiffness on normalized reinforcement loads

The effect of facing panel bending stiffness on the distribution of horizontal earth pressure behind the facing is shown in Figure 6. Also shown in this figure is the stress state corresponding to Rankine's active condition. Except at the lower part of the facing where the influence of the stiff foundation is significant, the horizontal earth pressures increase with the facing panel rigidity. The horizontal earth pressures are less than those given by theoretical Rankine active condition at intermediate depths and when the facing is very flexible.

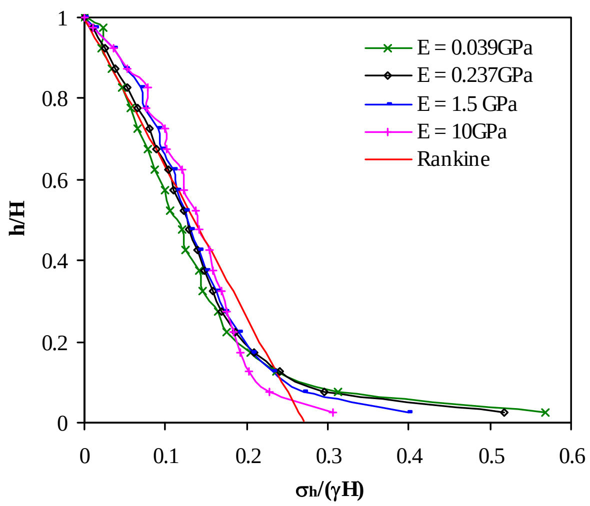

Figure 6. Effect of facing panel bending stiffness on normalized earth pressures

Effect of facing panel geometry for the same bending stiffness

Since the analyses presented in the last point showed that the facing panel rigidity has a great influence on the pattern of horizontal displacements and reinforcement tensile loads distribution, some additional analyses were performed to investigate the influence of facing panel thickness.

In order to generalize the conclusions of this study, the influence of the construction method, that is, the support provided to the face during wall construction, is implicitly considered. The effect of facing panel geometry is presented considering the fully supported and the incremental construction methods. The fully supported method corresponds to the case in which horizontal support is provided to the facing until the soil reaches the top. The supports are then released in sequence from the top to the bottom of the wall. The incremental method corresponds to the case in which support is only provided to each lift of soil as it is placed.

Figure 7 presents the influence of facing panel thickness, for the same bending stiffness (EI = 66.7 kNm^2), on the normalized horizontal displacements, considering the incremental method of construction (Figure 7a) and the fully supported method (Figure 7b).

Taking into account that the facing panel-foundation interface has the same characteristics for the different values of facing panel thickness, it is obvious that as lower is the thickness as larger are the horizontal displacements at the toe. The incremental method of construction leads to larger displacements at the toe. So, the influence of facing panel thickness is more expressive when the wall is incrementally constructed. The influence of facing panel thickness on the maximum horizontal displacement is not very significant. Nevertheless the bending of the panel increases with its thickness.

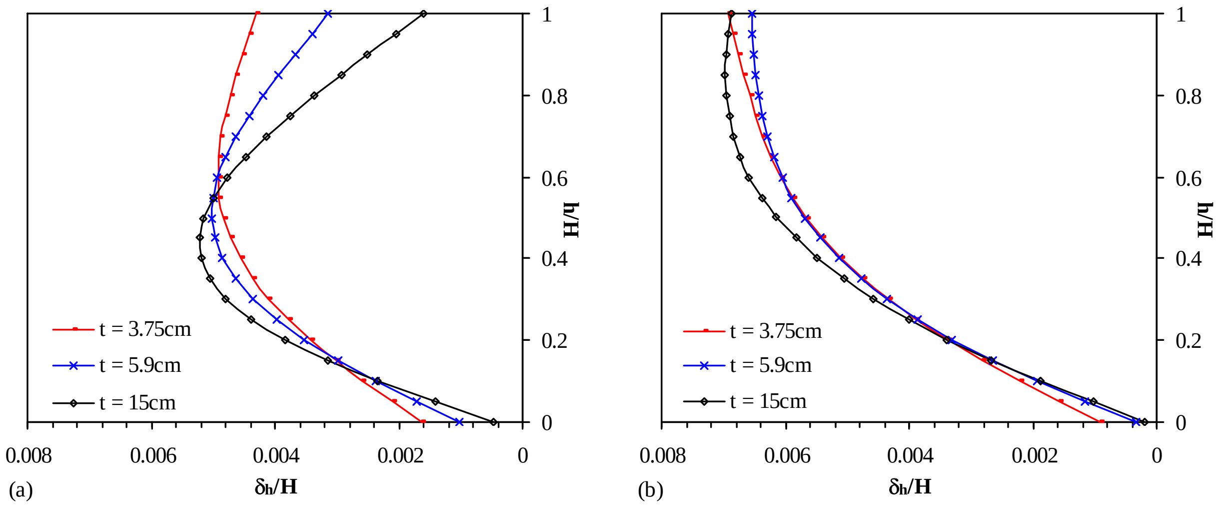

Figure 7. Effect of facing panel thickness on normalized horizontal displacements: a) incremental method of construction; b) fully supported method.

The maximum reinforcement tensile loads, mobilized along the reinforcement length, for distinct values of facing panel thickness are illustrated in Figure 8. Figure 8a presents the reinforcement loads mobilized on each reinforcement layer when the wall is incrementally constructed and Figure 8b is related to the fully supported method.

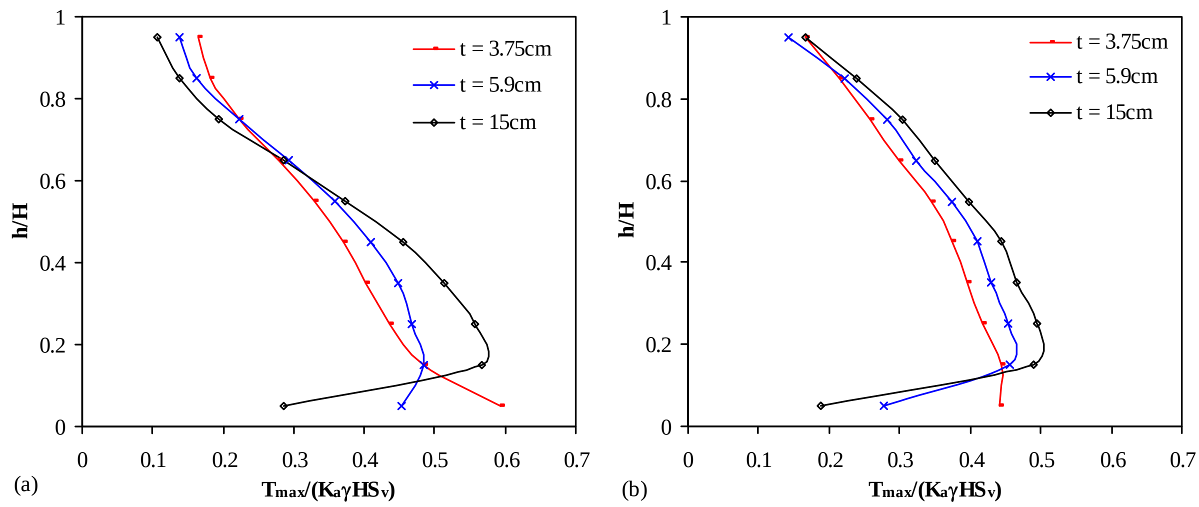

Figure 8. Effect of facing panel thickness on normalized reinforcement loads: a) incremental method of construction; b) fully supported method

As expected, on the basis of the results presented in Figure 7, the influence of facing panel thickness on normalized reinforcement loads is more significant when the incremental method of construction is used. The influence of the rigid foundation decreases with thickness. Note that the friction force mobilized at the face-foundation interface increases with thickness so, the tensile load mobilized on the lower reinforcement layer tends to decrease.

Influence of wall height

Effect of wall height for the same facing panel rigidity

In order to investigate the influence of wall height on the pattern of lateral displacements and reinforcement tensile load distribution, reinforced soil retaining walls with heights of 4.8 m, 6.0 m, 9.6 m and 12 m were numerically analysed. All these structures were constructed with the same vertical reinforcement spacing (S_v = 0.6 m) and facing panel bending stiffness (EI = 2812.5 kNm^2).

According to Rowe & Ho (1998) the most important parameter affecting horizontal deformation in reinforcement soil retaining walls is the reinforcement stiffness factor, λ. The reinforcement stiffness factor is defined as:

$$\lambda = \frac{J}{K_a \gamma H S_v}$$

Where J is the reinforcement stiffness, K_a is the active earth pressure coefficient, γ is the unit weight of the soil, H is the wall height and S_v is the vertical spacing between reinforcement layers.

The effect of wall height was numerically analysed considering that all the structures had the same reinforcement stiffness factor. Taking into consideration that the soil parameters and vertical spacing between reinforcement layers are equal for different wall heights, the reinforcement stiffness should increase with structure height. Values of 500 kN/m, 625 kN/m, 1000 kN/m and 1250 kN/m were considered for the reinforcement axial stiffness of reinforced walls with heights of 4.8 m, 6 m, 9.6 m and 12 m, respectively.

Figure 9 presents the normalized horizontal displacements of reinforced soil retaining walls with different heights and the same reinforcement stiffness factor. The displacements illustrated in Figure 9a are related to structures incrementally constructed while Figure 9b is related to the fully supported method.

Although the structures have the same reinforcement stiffness factor and facing panel rigidity, the bending of the panel decreases with wall height. The maximum value of the normalized horizontal displacement occurs for the shortest wall. These conclusions are independent of the construction method.

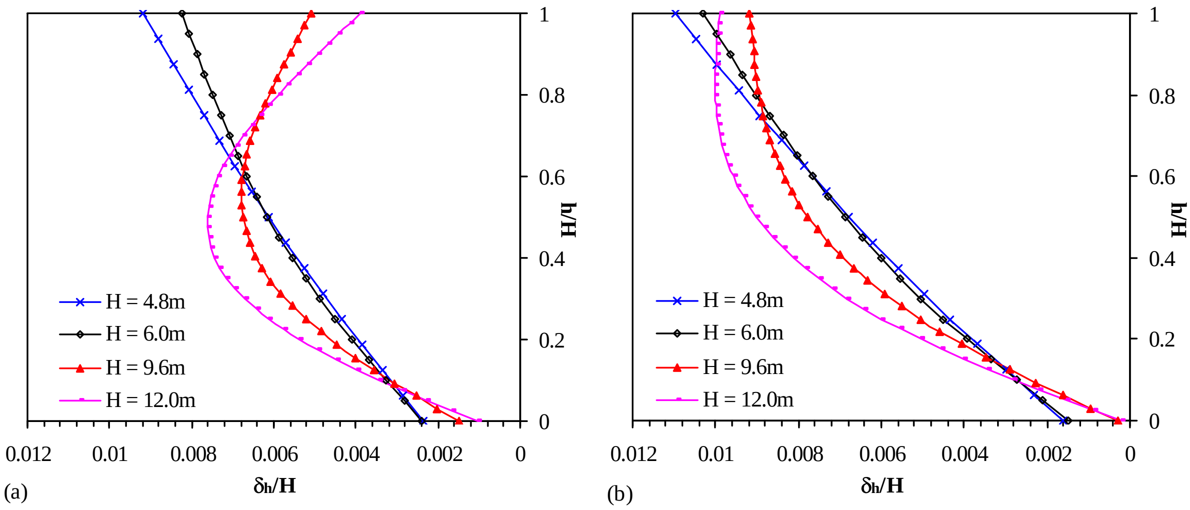

Figure 9. Effect of wall height on normalized horizontal displacements: a) incremental method of construction; b) fully supported method

The effect of wall height on the normalized maximum reinforcement tensile loads, mobilized along the reinforcement length is illustrated in Figure 10.

Effect of wall height for distinct facing panel rigidity

It was shown in the last point that construction of reinforced soil walls with the same reinforcement stiffness factor and equal facing panel bending stiffness but distinct height gives rise to different normalized horizontal displacements and reinforcement tensile loads. That means that facing panel bending stiffness should be confronted with wall height.

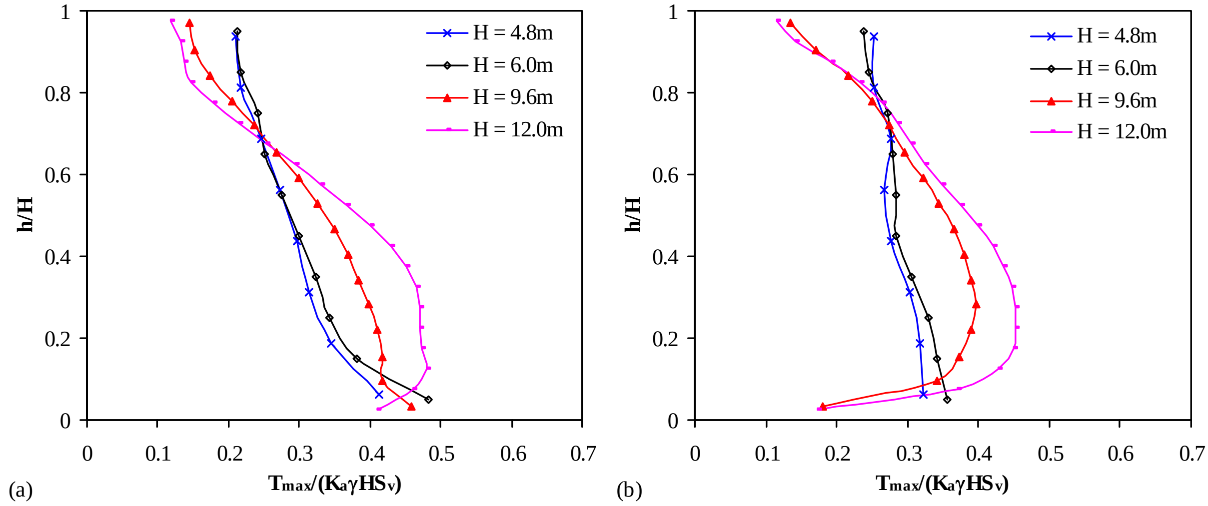

Figure 10. Effect of wall height on normalized reinforcement loads: a) incremental method of construction; b) fully supported method

To clarify the influence of facing panel rigidity for distinct wall heights, some additional analyses were performed. These analyses revealed that a reinforced soil retaining walls with height H_1 and facing panel bending stiffness $(EI)_1$ has a similar behaviour, relating to normalized horizontal displacements and normalized maximum reinforcement tensile loads, to a wall with height H_2 and facing panel bending stiffness $(EI)_2$, if the following equation is verified.

$$\frac{(EI)_2}{(EI)_1} = \left(\frac{H_2}{H_1}\right)^8$$

The analysis of Figure 11 and Figure 12 corroborates this conclusion. In fact, if the values of facing panel bending stiffness for different wall heights follow the last equation, normalized displacements and maximum tensile loads will be similar in pattern and in maximum value. This inference is independent of the construction method and restraining condition at the toe of the facing panel (Vieira 2008).

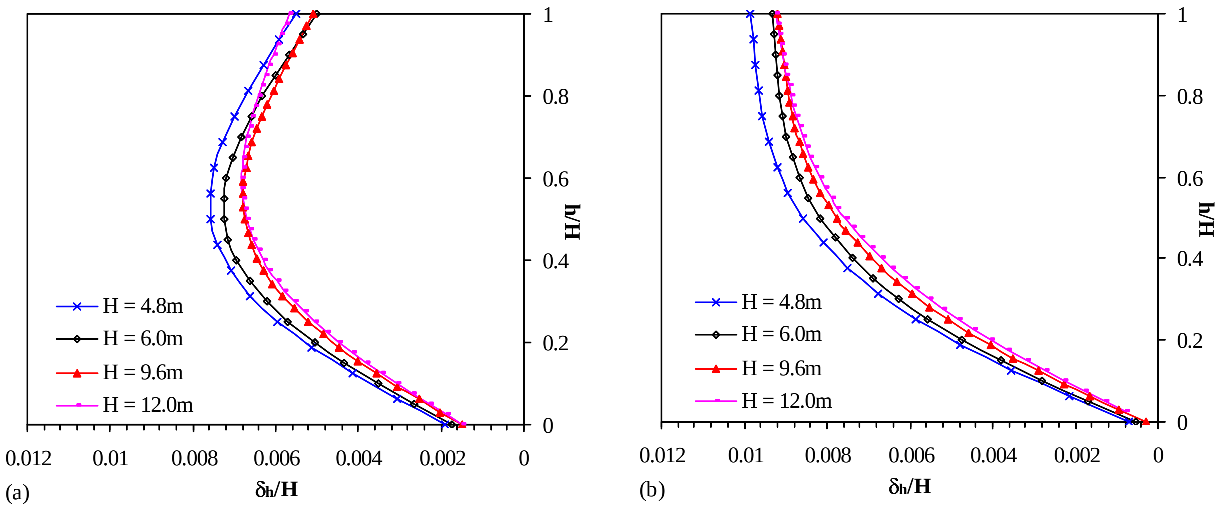

Figure 11. Effect of wall height on normalized horizontal displacements for distinct facing panel rigidity: a) incremental method of construction; b) fully supported method

Note that the results illustrated in Figure 11 and Figure 12 are related to reinforced soil retaining walls with continuous facing panel and the ratio presented in the last equation was achieved through the equations:

$$\frac{t_2}{t_1} = \left(\frac{H_2}{H_1}\right)^2$$

$$\frac{E_2}{E_1}=\left(\frac{H_2}{H_1}\right)^2$$

Where t_2 and E_2 are, respectively, the thickness and elastic modulus of the facing panel for the wall with height H_2 and t_1 and E_1 have similar meanings referred to wall with height H_1.

If the ratio between the values of facing panel bending stiffness obeys the equation previously presented but the last two equations are not observed, the agreement achieved is not so perfect (Vieira 2008).

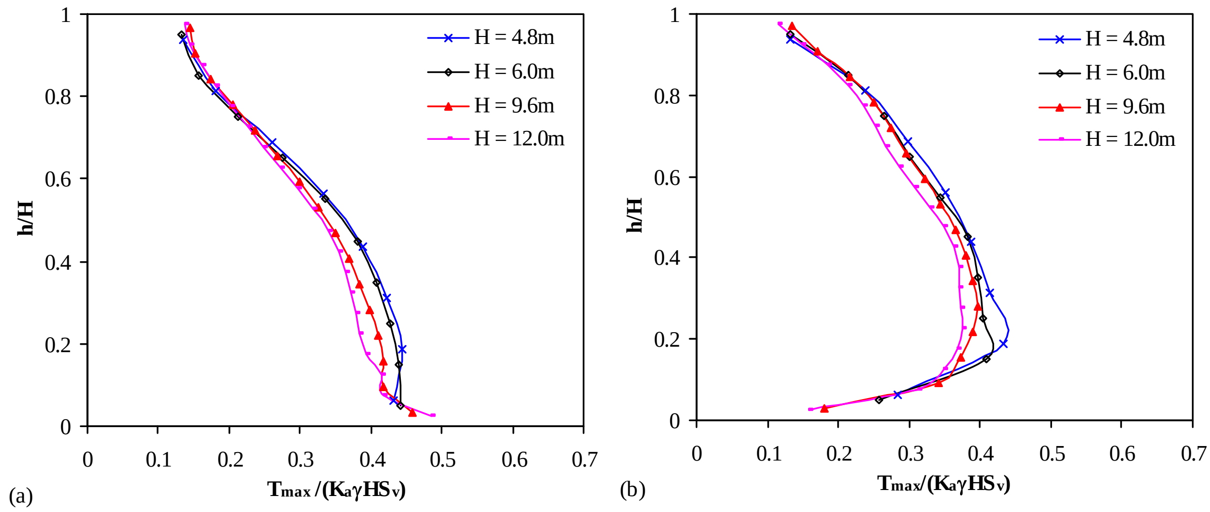

Figure 12. Effect of wall height on normalized maximum reinforcement loads for distinct facing panel rigidity: a) incremental method of construction; b) fully supported method

CONCLUSIONS

This numerical study leads to the following conclusions:

- FLAC numerical results for a reference geosynthetic reinforced soil wall are in close agreement with those reported in the literature using FEM
- The pattern of the normalized horizontal displacements and the reinforcement tensile load distribution are largely influenced by facing panel bending stiffness
- When the facing panel rigidity increases the location of maximum horizontal displacement rises on wall height
- The influence of facing panel thickness for the same bending stiffness is more significant when the wall is incrementally constructed
- It is very important to consider the facing panel bending stiffness with wall height. A single value of EI does not mean "the same" for different wall heights.

REFERENCES

Bathurst, R. J. & Hatami, K. 1998. Seismic Response Analysis of a Geosynthetic-Reinforced Soil Retaining Wall. Geosynthetics International. Special Issue on Geosynthetics in Earthquake Engineering, 5, 1-2, 127-166.

FHWA (2001), Mechanically Stabilized Earth Walls and Reinforced Soil Slopes. Design and Construction Guidelines. FHWA-NHI-00-043, Federal Highway Administration, US Department of Transportation, Washington D.C.

Itasca. 2002. FLAC - Fast Lagrangian Analysis of Continua. Version 4.00, Itasca Consulting Group, Inc., USA.

Rowe, R. K. & Ho, S. K. 1997. Continuous Panel Reinforced Soil Walls on Rigid Foundation. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 123, 10, 912 - 920.

Rowe, R. K. & Ho, S. K. 1998. Horizontal deformation in reinforced soil walls. Canadian Geotechnical Journal, 35, 312-327.

Vieira, C. S. 2008. Geosynthetic reinforced soil retaining walls and slopes. Seismic behaviour and design methodologies. PhD Thesis, University of Porto, pp. 575 (in Portuguese).