Seismic Response of Geosynthetic Reinforced Soil Retaining Walls: Influence of Facing Panel Properties

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***Abstract*- The paper presents a numerical study carried out to analyse the influence of the facing panel properties on the seismic response of a 6 m high geosynthetic reinforced soil retaining wall with continuous facing panel. The effect of the restraining condition at the toe of the facing panel and its bending stiffness are analysed. The lateral displacements and the reinforcement tensile loads at the end of construction and after a potential earthquake are analysed and compared. The numerical analyses showed that the facing panel bending stiffness has a significant influence on the pattern of lateral displacements and on reinforcement tensile loads.**

Keywords*- *Geosynthetics; Reinforced Soil Retaining Walls; Facing Panel Stiffness; Numerical Modelling; Seismic Loading

I. INTRODUCTION

The performance of geosynthetic reinforced soil retaining structures in the earthquakes occurred in the last decades has been diverse. The Hyogoken-Nambu Earthquake caused serious damage to conventional masonry retaining walls, unreinforced concrete gravity type retaining walls and cantilever type steel-reinforced concrete retaining walls, while geogrid-reinforced soil retaining walls, having a full-height concrete facing, performed very well during the earthquake [1]. On the other hand, the Chi-Chi earthquake, in Taiwan, caused serious damage to reinforced-soil retaining walls using keystones as facing [2].

The good performance of these structures is usually justified by the extensibility of the geosynthetics, which allows significant levels of strain without failure, and by the conservative design methods. However, it must be noted that this type of structures has been an increasing applications in roads, railways, and bridge abutments, where a strictly control of strains is demanded. So it is important to improve the knowledge related to the seismic behaviour of these structures.

The effect of the seismic loading on the required geosynthetic strength is based, usually, on pseudo-static analyses. These analyses are, frequently, considered as conservative, since transitory earthquake acceleration is assumed to act permanently on the structure, they are dependent only on peak ground acceleration and disregard the effects due to duration of seismic action, frequency, foundation condition, and stiffness of the reinforcement or facing type.

In this work the two-dimensional finite difference program Fast Lagrangian Analysis of Continua (FLAC) was used to carry out parametric analyses [3]. FLAC is an explicit dynamic code, suitable for modelling large distortions and dynamic response of earth structures. This code has also been used to investigate the seismic response of geosynthetic reinforced soil structures by other authors ([4-6]).

II. NUMERICAL MODELLING OF THE CONSTRUCTION

A. General Aspects

This numerical study regards a geosynthetic reinforced soil retaining wall of height H = 6m with 10 horizontal reinforcement layers, uniformly spaced, of length L = 4.2 m, attached to a continuous facing panel. The wall and soil regions were supported by a stiff foundation.

The geogrid 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 [7] for static design of geosynthetic reinforced soil walls.

The numerical grid is illustrated in Fig. 1. The width of the backfill was extended to 35 m beyond the back of the facing panel and, to avoid the reflection of the waves back into the model, absorbing boundaries (free-field conditions, [3]) were applied to left and right side vertical boundaries.

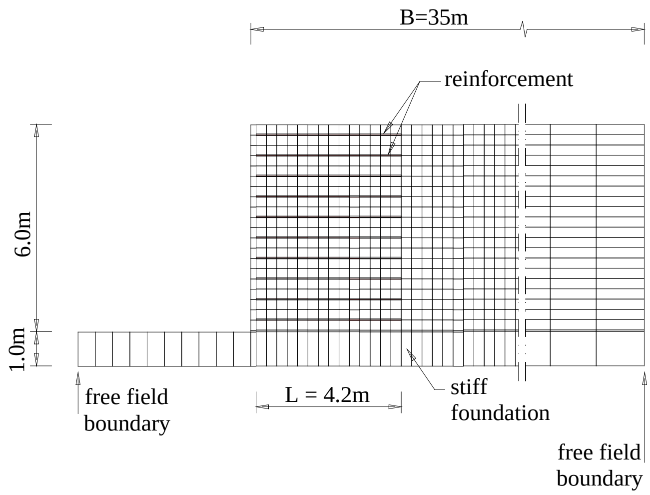


Fig. 1 Numerical grid for the sliding case

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 $\phi = 35º$ and the unit weight $\gamma = 22$ kN/m^3. The bulk and shear modulus values of the soil were K = 50.0MPa and G = 23.1MPa, respectively. The facing panel thickness was considered equal to 0.15 m and it was assumed an elastic material. The effect of the bending stiffness of the facing panel will be presented in sequence.

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 geogrid was taken equal to 1000 kN/m.

The interface between the facing panel and the reinforced soil 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 was constructed in 20 layers and it was assumed that the wall facing was fully supported in the horizontal direction during construction. The panel supports were released in sequence from the top of the structure.

As regards the restraining condition at the toe of the facing panel, two conditions were analysed. The facing panel could be hinged at the toe (Fig. 2a) or free to slide (Fig. 2b). The hinged case (Fig. 2a) corresponds to a situation in which the facing panel is fixed to the foundation but is free to rotate. For the sliding case (Fig. 2b), the facing panel is free to slide horizontally and rotate about the toe. In this case the facing panel was seated on a thin layer of soil, with friction angle equal to 20º.

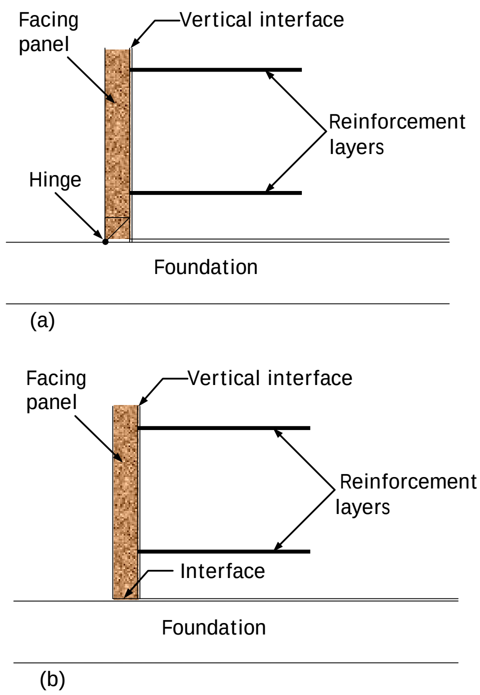


Fig. 2 Restraining conditions at the toe of the facing panel: (a) hinged; (b) free to slide

B. Influence of the Restraining Condition at the Toe of the Facing Panel

The influence of the restraining condition at the toe of the facing panel on the lateral displacements and reinforcement tensile loads at the end of construction is illustrated in Fig. 3(a) and 3(b), respectively. Fig. 3(b) presents the connection loads (black lines) and the maximum tensile loads reached through the reinforcement length. The reinforcement loads are greater at the connections for both restraining conditions.

To present and compare the results, the lateral displacements (δ_h) of the facing panel were normalized by the wall height (H). The reinforcement loads appear normalized by γHS_v where, γ is the unit weight of the soil, H is the wall height and S_v is the vertical spacing between reinforcement layers.

The pattern of the lateral displacements for the two conditions is similar; however, the sliding case leads to greater lateral displacements. As expected, the reinforcement tensile loads are larger, particularly near the toe, when the base of the facing panel is free to slide.

More details about the influence of the restraining condition at the toe of the facing panel can be found in [8].

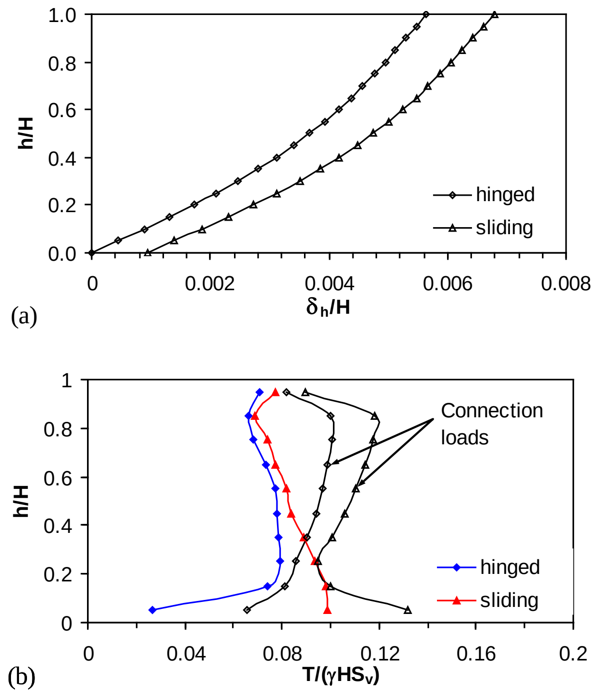


Fig. 3 Influence of the toe restraining condition (end of construction): (a) on the normalized lateral displacements; (b) on the normalized reinforcement loads

C. Influence of the Facing Panel 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. A wide range of facing stiffness values is, obviously, associated to this diversity of facing systems

To evaluate the effect of facing panel bending stiffness on the behaviour of geosynthetic reinforced soil retaining walls with continuous facing panel, a parametric study was 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: 11.0kNm^2, 66.7kNm^2, 421.9kNm^2 and 2812.5kNm^2. These values were achieved with elastic modulus of 0.039GPa, 0.237GPa, 1.5GPa and 10GPa, respectively.

The influence of facing panel stiffness on the horizontal displacements and maximum reinforcement tensile loads at the end of construction is illustrated in Fig. 4. It can be observed that the bending stiffness of the facing panel (EI) 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 bending stiffness of the facing panel increases from 11.0kNm^2 to 421.9kNm^2, the maximum lateral 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 [9] showed that increasing a hundredfold of the wall bending stiffness, the maximum horizontal displacement of the facing decreases 15%.

Fig. 4(b) shows the maximum reinforcement tensile loads, mobilized along the reinforcement length, for distinct values of facing stiffness. 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.

Although the influence of the facing panel stiffness on the maximum lateral displacement is not very significant, the maximum reinforcement tensile load mobilized increases considerably when the facing panel become more flexible.

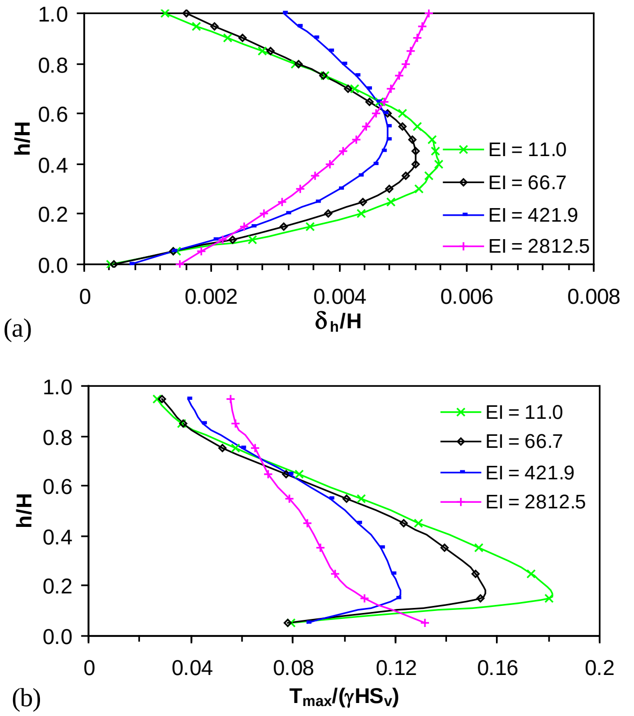


Fig. 4 Effect of facing panel bending stiffness: (a) on the normalized lateral displacements; (b) on the normalized maximum tensile loads

III. SEISMIC BEHAVIOUR

A. *Seismic Action*

Fig. 5 presents an earthquake ground motion artificially generated according to Portuguese National Annex of Eurocode 8 [10] for the greater seismicity area of Portugal, considering an earthquake with moderate magnitude, small focal distance (close earthquake) and ground type B (deposits of very dense sand, gravel or very stiff clay). This earthquake was considered as the input motion for the numerical analyses herein presented.

The horizontal displacements obtained by double integration of the earthquake ground motion presented in Fig. 5 are illustrated by the red line (without correction) in Fig. 6. Without correction, significant residual displacements occur at the end of the motion. To avoid these unreal large displacements at the end of the dynamic action, a baseline correction should be performed. A low frequency wave is determined which, when added to the original history, produces a final displacement equal to zero (black line in Fig. 6). The velocity and acceleration time histories with and without baseline correction remain similar.

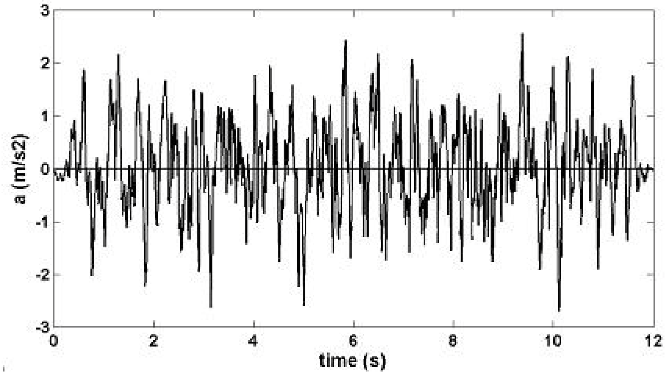


Fig. 5 Earthquake ground motion considered as input loading

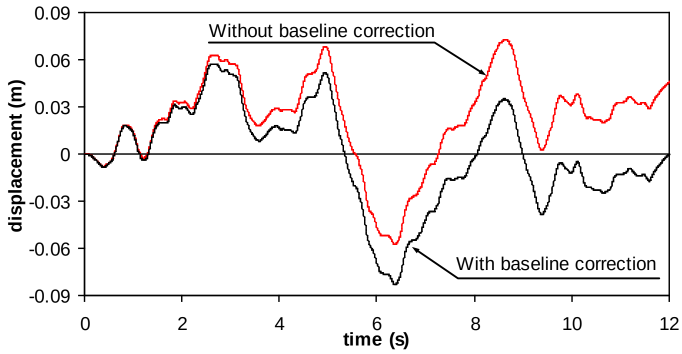


Fig. 6 Baseline correction to avoid unreal residual displacements

B. *Influence of the Restraining Condition at the Toe of the Facing Panel*

Fig. 7 presents the normalized lateral displacements of the wall facing and maximum reinforcement tensile loads at the end of the earthquake motion for a hinged or a sliding toe facing panel. As expected, sliding case leads to greater lateral displacements; however, the top lateral displacement is nearly the same. As a result of greater facing panel displacements near the toe of the wall, the reinforcement load in the bottom layer is significantly larger for the sliding case. In the other reinforcement layers the differences are not significant.

The time histories of the horizontal displacements of the facing panel at the bottom layer level, normalized by the wall height, are presented in Fig. 8 (a) for the two restraining conditions. Fig. 8(b) illustrates the time histories of the connection loads at the bottom layer for hinged and sliding toe facing panel. The connection loads accumulated with time during the seismic motion. The greater connection load, which occurred for the sliding case, is partly a consequence of the load measured at the end of construction (see also Fig. 3b). For the sliding case the connection load at the bottom layer increased approximately four times during the seismic loading while, for the hinged toe condition, the increase was six times the value measured at the end of construction.

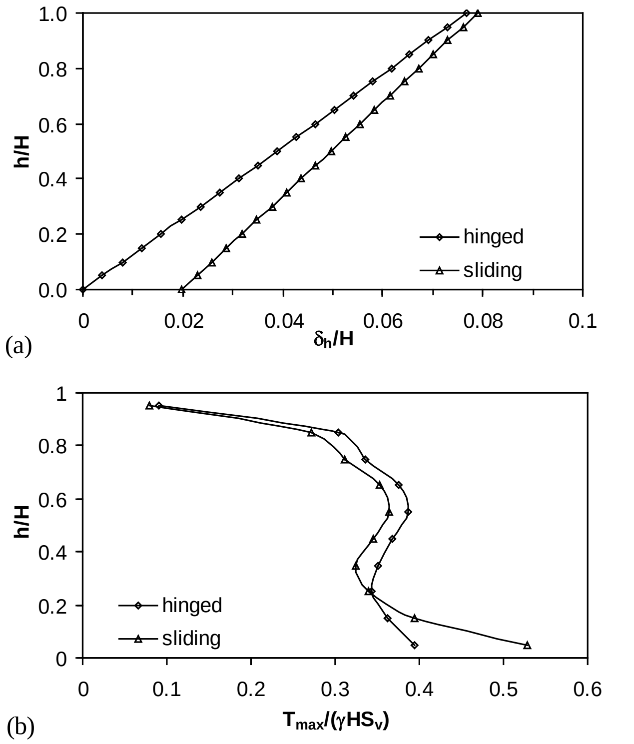


Fig. 7 Influence of the restraining condition at the toe: (a) on the normalized lateral displacements; (b) on the normalized maximum reinforcement loads

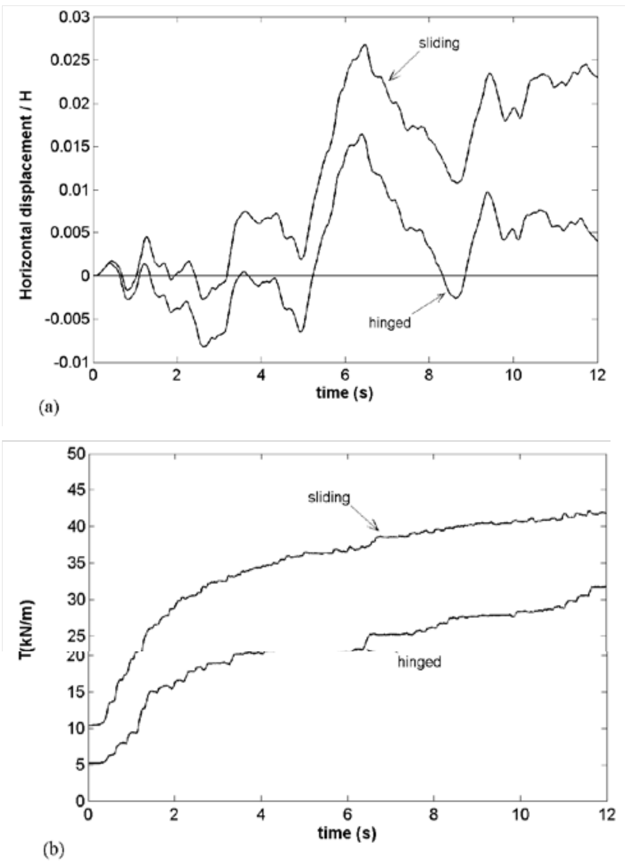


Fig. 8 Time histories for the bottom reinforcement layer: (a) normalized facing panel horizontal displacement at reinforcement level; (b) connection loads

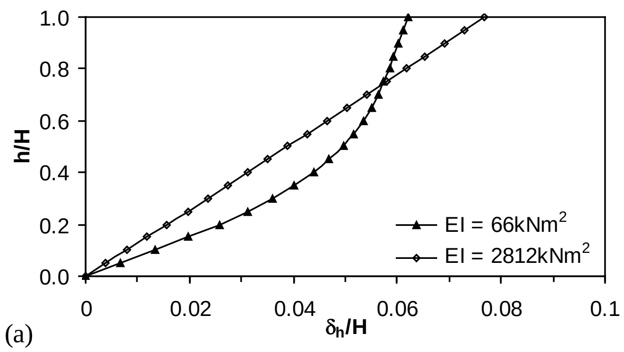
C. Influence of Facing Panel Stiffness

In what concerns the effect of the facing panel bending stiffness (EI) on the seismic behaviour of the retaining wall, two situations were analysed: a flexible facing panel with bending stiffness equal to 66.7kNm^2 and a rigid facing panel with EI = 2812.5 kNm^2. The thickness of the facing panel was assumed constant and the elastic modulus of the material was changed.

Fig. 9 illustrates the influence of facing panel stiffness on the normalised lateral displacements and maximum reinforcement tensile loads, considering the facing panel of the retaining wall with a hinged toe. The bending of the facing panel, when it is more flexible, is visible in Fig. 9. More or less unexpected, the top lateral displacement of the panel increased with facing stiffness. Reduced-scale shaking table tests reported by [11] showed that, for model walls with a thick facing panel, the top lateral displacement was larger than those recorded in models with a thin facing panel. According to [11] this occurrence was due to the greater destabilizing inertial forces developed in the thick facing panel models. Nevertheless, the results presented in Fig. 9 are related to facing panels with equal weight, therefore the destabilizing inertial forces theoretically are the same. In fact, the bending of the flexible facing panel leads to smaller lateral displacements at the upper zone of the wall.

Regarding the normalised maximum reinforcement tensile loads (Fig. 9b), it can be observed that the increase of facing panel stiffness leads to greater reinforcement loads at upper layers and the opposite trend at lower reinforcement layers. For the flexible facing panel, the maximum reinforcement load distribution tends to a triangular shape.

The time histories of the connection loads at the bottom reinforcement layer for the two values of the facing panel stiffness, assuming a hinged toe, are illustrated in Fig. 10(a). As above-mentioned, the decrease of facing panel stiffness leads to greater reinforcement load at the bottom layer. The time histories of connection loads normalised by the connection load at the end of construction (To) are presented in Fig. 10(b). Fig. 10(b) shows that the time histories of the normalised connection loads for the bottom reinforcement layer are similar. This evidence results from the lower value of the connection load at the bottom reinforcement layer for static conditions (end of construction), reached when the facing panel is rigid (see the first instant of the time history presented in Fig. 10a). Note that at the end of the seismic loading, the normalised connection load is slightly larger for the rigid facing panel (EI = 2812.5 kNm^2).



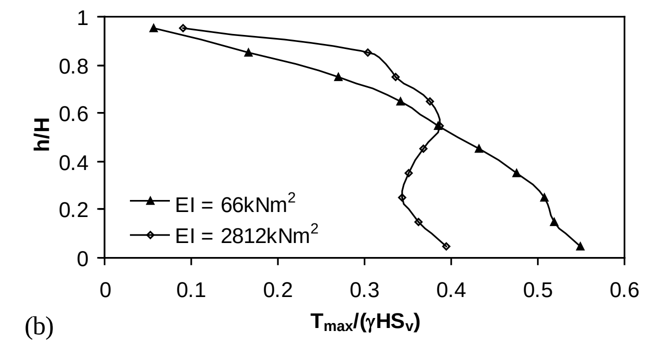


Fig. 9 Influence of facing panel stiffness, for a hinged toe, on: (a) the normalized lateral displacements; (b) the normalized maximum reinforcement loads

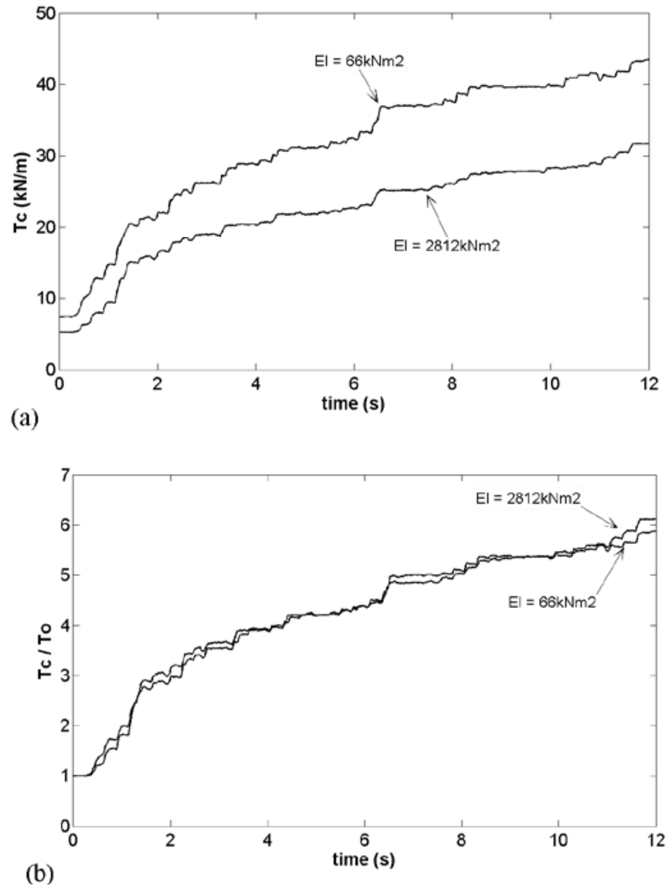


Fig. 10 Influence of facing panel stiffness (hinged toe): (a) connection load histories at the bottom reinforcement layer; (b) connection load normalized by the load at the end of construction (To)

IV. CONCLUSIONS

A numerical study was performed to analyze the influence of the facing panel properties on the static (end of construction) and seismic response of a geosynthetic reinforced soil retaining wall with continuous facing panel. This study led to the following conclusions:

- when the toe of the facing panel is free to slide, it is necessary special attention to the tensile loads developed at the lower reinforcement layers;
- the pattern of the horizontal displacements of the facing panel and the reinforcement tensile loads distribution are largely influenced by facing panel bending stiffness;
- with the increase of the facing panel bending stiffness, the location of maximum horizontal displacement rises on wall height;
- a flexible facing panel may lead to smaller lateral displacements at the upper part of the wall but greater tensile loads at lower reinforcement layers;

It should be noted that the conclusions of this study are limited to geosynthetic reinforced soil retaining walls with continuous facing panel, uniform backfill and rigid foundation.

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