Face Deformation of Walls Reinforced with Geosynthetics

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ABSTRACT: Nowadays, retaining walls reinforced with geosynthetics are already an accepted alternative to gravity walls and other conventional retaining structures. Design of these structures has also evolved, and there are several design methods capable of verifying the global stability of the structure – limit equilibrium methods. However, geosynthetic reinforcement elements are extensible and therefore they work through the soil-reinforcement interface that develops due to the deformation of the wall itself and its elements. This deformation needs to be controlled to avoid functional and structural problems. The study described in this work aims to evaluate the feasibility of a proposed method to calculate the face deformation and pressures acting on the rear face of brick retaining walls reinforced with geosynthetics. The expeditious method was applied to walls with different characteristics presented in literature. The calculated horizontal deformations of the face compares well with those measured in the walls. It can be concluded that the method under consideration can be a good option for future research and practical applications, since the alternative and commonly used solution - numerical modelling - is far more complex and expensive.

Keywords: Face deformation, retaining walls, soil reinforcement, design method

1 INTRODUCTION

The soil reinforcement is a recognized very old technique that has undergone major advances. After the "Reinforced Earth" wall proposed by Henry Vidal in the 60's, who also introduced the modern soil reinforcement concept, the retaining wall reinforced with geosynthetics appearance, showed to be a good alternative to the metallic walls of Vidal.

The behavior of retaining structures reinforced with geosynthetics has been a topic of great interest for the geotechnical community. Various laboratory and field studies, complemented very often with numerical analysis have been carried out: Lee et al, 1973; Osman et al., 1979; Juran and Christopher 1989; Pinto, 1992; Dalton, 1977; Walsh, 1987; Jewell, 1987. All of these investigations have the same goal: the study and comparisons of the observed behavior in the laboratory with the behavior observed in the field. This type of structure does not depend only on isolated characteristics of each of its constituents, but depends greatly on the interaction between them. Therefore it is necessary to study the behavior of these structures in order to identify all factors that may affect its behavior, allowing to predict their influence for design. As many of those factors (soil-reinforcement interface, friction developed over the face and the wall foundation, the quality of the connection between the reinforcements and the face, soil backfill, and so on) are difficult to quantify, the design process is still complex.

Despite all the knowledge achieved during many years of study, design of reinforced walls with geosynthetics, is still a challenge task. The characterization of the soil is one of the most important stages in any geotechnical work, but so it is the reinforcing material and the face wall. Since it is through the soil-reinforcement interface that soil stresses are transmitted to the reinforcement, the deformability of these elements is a key issue in the efficiency of the reinforcement. The reinforcement in retaining walls reinforced with geosynthetics are extensible, and therefore it is particularly important to consider the compatibility deformations of the various elements in order to predict and control the deformation suffered by the wall (Serviceability Limit State).

The current design methods are based, in general, on the equilibrium limit of the structure to ensure its overall stability. Correia (2003) adapted some of the existing design methods for application to earth retaining walls reinforced with geosynthetics. This researcher showed the feasibility of their use for the internal stability of brick masonry walls reinforced with geosynthetics studied by Pinto (1992). Nowadays there are two types of methods that take into account the deformation, to ensure the proper functioning of the structure (Serviceability Limit State - SLS), the numerical methods (which require a rigorous characterization of soil and other constituents of the wall, together with many often a time-consuming, complex and costly analysis calculation), and the expeditious methods.

Correia (2003) has also developed an expeditious method, based on a simple theoretical model to predict the face deformation of brick retaining walls reinforced with geosynthetics, based on laboratory studies of Pinto (1992). This method was validated by the similarity between the results obtained by the proposed method and the deformations measured in these walls (small scaled model walls) for a given value of surcharge load (2,445 kPa), which is lower than the corresponding to SLS defined by Pinto (1992).

The method proposed by Correia requires data for the geometry of the wall and some characteristics of the face of the wall, reinforcing elements and the soil of the backfill, and it provides the earth pressures diagram and consequent deformation of the face. However, the simplicity of the simulation of the problem, and the necessity of low level of data, requires definitely a greater need for validation of the theoretical model based on laboratory models or case studies. It is with this objective that the study described herein applies the method proposed by Correia to the brick retaining walls reinforced with geosynthetics, under different levels of surcharge, below and above to the observed SLS surcharge.

2 BRICK RETAINING WALLS REINFORCED WITH GEOSYNTHETICS

The walls studied by Pinto (1992) through a laboratory test program were small scaled model walls, similar to walls proposed by Dalton 1977 (Figure 1): walls reinforced with sheets of geosynthetics, vertically spaced, extended horizontally from the wall face into the ground. The connection of the sheets of geosynthetics to the wall is made in the mortar joint between the brick courses of the wall face. Tests were performed inside a rigid steel tank with side walls of glass, 490 mm high, 630 mm long and 240 mm wide. The size of the walls built inside the tank were 300 mm high x 20.5 mm thick and 240 mm wide. The rigid foundation was materialized with a row of bricks glued to the base of the test tank.

Pinto and Cousens (1999) tested several of these walls, with and without reinforcement, and compared the results with those of Walsh prototype, thus validating the reduced model and confirming a minor scale effect.

The soil of the backfill was a medium sand, with a peak angle of friction of 40˚, a residual angle (constant volume) of 35˚ and a density of 16.3 kN/m^3 after dynamic compaction. The interaction between soil and the reinforcing elements showed a peak angle of friction of 36˚. The reinforcement was a non-woven geotextile, with a mass of 56 g/m^2 and a thickness of 0.3 mm with a load capacity range between 1.4 - 1.8 kN/m width, and an elongation at break of 15%. The face of the wall was made by small bricks sawn from full size bricks, with final dimensions of 43 mm x 20.5 mm x 13 mm and a density of 24 kN/m^3. The angle of friction of the interface between the soil and the bricks was 37˚.

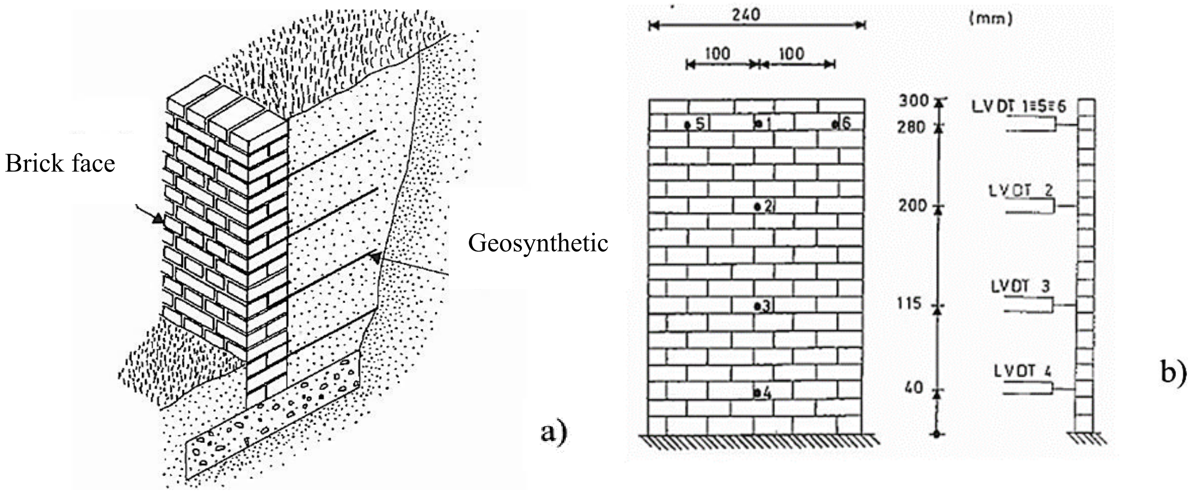


Figure 1 – a) Walls suggested by Dalton in 1977; b) walls built by Pinto in 1992 (Pinto 1992).

The construction of the wall was carried out in some different stages: first, the face of the wall was built, placing the geosynthetics with the predefined vertical spacing, at the middle of the mortar joint, and then the wall was left for the mortar curing; 24 hours after that, the placement of the soil backfill was carried out in 30 mm layers, compacting each layer and positioning the reinforcing elements into the backfill when necessary (three vertical reinforcement spacing's were tested: 2, 3 and 4 brick courses and two reinforcing lengths: 80 and 120 mm). Finally, the application of a uniformly distributed surcharge was applied through a water mattress placed on the top of the backfill. The surcharge was increased in increments of about 0.45 kPa to achieve maximum allowed surcharge (24 kPa) or the collapse of the structure (ultimate limit state – ULS).

The small models were monitored to measure, among other things, the wall movement. Six LVDT's were used on the face (Figure 1b): 4 in the middle, vertically, for the vertical deformation profile; 2 in the top, horizontally, to measure a possible twisting of the face of the wall.

According to Pinto (1992), the brick retaining walls reinforced every 2 or 3 bricks courses showed a complex type of movement, with the failure being slow and gradual, and some of the walls even reached the maximum surcharge level without collapsing; during the application of surcharge a crack appeared in a mortar joint that accommodates the reinforcement, approximately at the middle height of the wall, a situation that was defined by Pinto as the service limit state (SLS) of the structure. Most of the reinforced brick walls reinforced every 4 brick courses does not develop the crack at the middle height and the movement is similar to that of unreinforced walls. However, unlike these walls, they support a surcharge load before the collapse (ULS).

3 EXPEDITIOUS METHOD FOR PREDICTION THE WALL DEFORMATION

The expeditious method developed by Correia (2003) was improved to allow, not just the verification of the internal safety, but also the verification of its functional equilibrium. The face of the wall is represented by a simply supported beam with the reinforcing elements being simulated by flexible supports (spring type). The foundation wall is defined by a double support on the base of the beam and it has a degree of freedom to allow a rotational movement, observed in laboratory studies. The deformability of the simply supported beam is controlled by the flexural stiffness of the wall face, which depends on the mortar-brick bond strength. The flexible support is simulated with rods which are characterized based on the tensile strength and the axial stiffness of the reinforcing elements.

The expeditious method cannot simulate directly the effect of the confining stress on the stiffness of geosynthetics along the height of the wall. Therefore, in a first stage, Correia kept the stiffness of all the reinforcing elements with the same constant value. The simply supported beam is subject to a theoretical diagram of earth pressures that aims to simulate the effect of the deformability of the components and compatibility of deformations required for equilibrium. Figure 2 illustrates, schematically, the Correia model (2003).

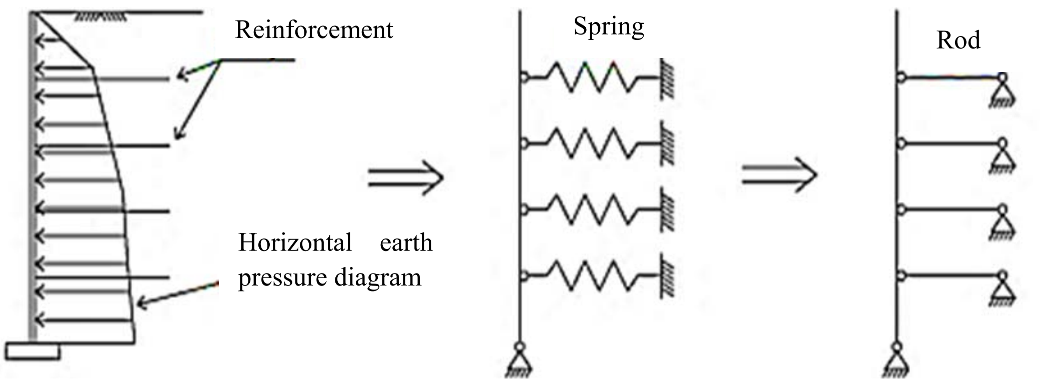


Figure 2 – Theoretical model proposed by Correia (2003).

The characterization of the theoretical diagram of the earth pressures is an important step to obtain a satisfactory model for predicting deformation of the face. This must simulate the observed pressure diagram for this type of walls as better as possible. Juran and Schlosser (1978) and Osman et al. (1979) found that the diagram of horizontal effective stresses was not linear along the height of the wall, standing with a value close to the correspondent to the at rest earth pressure coefficient (K_0) at the top and the close to the corresponding to the active earth pressure coefficient (K_a) at the base. This conclusion was also confirmed by Pinto studies (1992). Furthermore, it was found that the effective stresses experience a sudden decrease always when it reaches a reinforcement element level, increasing immediately after the reinforcement until the next reinforcement element level and so on, corroborating also the observations made by Tsagareli (1969).

Figure 3 shows the variation of the earth pressure coefficients K_0 and K_a estimated by Juran and Schlosser (1978) and Osman et al. (1979) and a representative scheme of earth pressures diagram considered by Correia (2003).

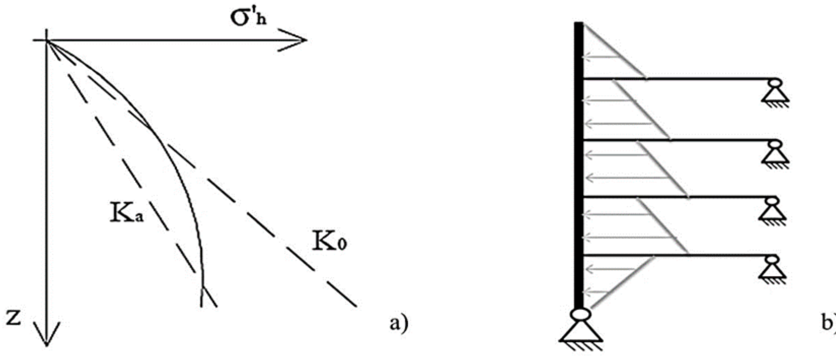


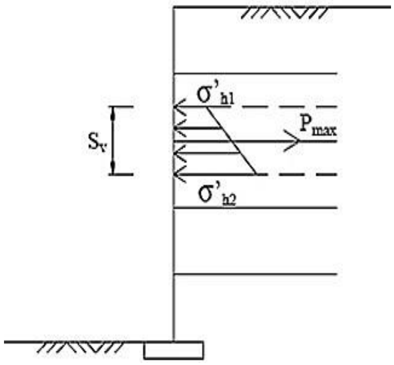
Figure 3 – a) Variation of the horizontal effective stresses along the height of the wall; b) scheme of the stress diagram (adapted from Correia, 2003)

Osman (1977) conducted a study, based on energy equilibrium, which allowed Correia (2003) to estimate the maximum tensile force, T_{max}, mobilized on each reinforcement level (Equation 1). In this equation, K represents the coefficient correspondent to the at rest state (K_0) or to the active state (K_a) if immediately before or if immediately after the reinforcement level, respectively; L = the length; σ'_v = the effective vertical stress at the reinforcement element level; S_v and S_h = the reinforcement vertical and horizontal spacing, respectively; H = the total height of the wall; z = the height from the top of the backfill.

$$T_{m\acute{a}x}(z) = \sqrt{\frac{6\times K^{0.5}}{L}} \times \sigma'_v \times S_v \times S_h \times \sqrt{H - z} \quad (1)$$

Based on the maximum mobilized tensile force in reinforcement, and considering the equilibrium with the horizontal effective stresses in the zone of influence of the reinforcing element under analysis (Figure 4), the diagram of horizontal effective stresses acting for each spacing between reinforcing elements is achieved. From Juran and Schlosser (1978) and Osman et al. (1979), it is possible to estimate the variation of the horizontal effective stresses by Equation 1, replacing the coefficient K by K_0 and K_a, respectively for the effective stresses acting immediately before and after each reinforcement level. The theoretical diagram of the horizontal effective stresses acting on the rear face of the wall is defined by the distribution of T_{max} by the area of influence of each reinforcement (Equation 2).

The model was tested with a computer program, very easy to use, designated by OSSA2D which was developed at the University of Liège. It is an elastic linear analysis program for planar structures based on the displacement method. It only requires the introduction of a structural diagram, similar to Figure 3b), and some data concerning the reinforcing elements and the face. For the geosynthetics it is necessary to know the thickness (area), the deformability modulus (associated with the axial stiffness of the reinforcing elements), and the strength of the material that corresponds to the tensile strength of the reinforcements. As far as the face is concerned, it is necessary to know the thickness (the area and the moment of inertia influencing the compressibility of the face), weight, deformability modulus (resulting from the flexural stiffness of the face) and, where relevant to the problem, strength of the joints between the elements of the face. The structural analysis is usually performed by meter wide and provides the reactions on the supports, diagrams of bending moments, strain diagram of the elements and all displacements, in particular, the horizontal displacements (the single parameter analyzed in this study).



$$\sigma'_h = \frac{T_{max}(z)}{S_v \times S_h} \tag{2}$$

Figure 4 – Equilibrium scheme for the calculation of the horizontal effective stress (Correia, 2003).

4 APPLICATION OF THE EXPEDITIOUS METHOD TO THE BRICK RETAINING WALLS REINFORCED WITH GEOSYNTHETICS

The expeditious method proposed by Correia (2003) was applied to all brick retaining walls reinforced with geosynthetics built on rigid foundations, therefore all geometries were considered (all reinforcement lengths and reinforcement vertical spacings) of the reinforcing elements tested by Pinto (1992) (Table 1).

During laboratory tests, different levels of surcharge were applied to the reinforced walls - the surcharge increased in increments equivalent to the weight of a 0.03 m thick layer of soil embankment. Table 2 indicates the level of surcharge for each wall necessary to reach the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS). This Table also includes the value of the additional surcharge that each wall can support between the development of the crack (SLS), whose location from the top of the wall is also shown (Z_{crack}), and the collapse (ULS).

Table 1 – Walls studied by Pinto (1992) and used in the application of the Correia's model

Wall's code	Reinforcement length (mm)	Reinforcement vertical spacing (mm)
6R8-2	80	2 brick courses (about 30 mm)
9R8-3		3 brick courses (about 45 mm)
12R8-4		4 brick courses (about 60 mm)
14R12-2	120	2 brick courses (about 30 mm)
17R12-3		3 brick courses (about 45 mm)
21R12-4		4 brick courses (about 60 mm)

Tables 3 and 4 summarize the characteristics considered in the application of the expeditious method. As far as the reinforcement characteristics are concerned an attempt to introduce the effect of reinforcement confinement and embedment was made. This tentative was designated as OSSAD (Geo Var) in opposition to the study without the consideration of these effects designated as OSSAD (K_0). On OSSAD (Geo Var), the deformability modulus considered (Table 4) for the first reinforcement level (at top) was different from the other reinforcing elements.

Table 2- Summary of the behaviour observed by Pinto (1992) on the model walls tested

Wall's code	Serviceability Limit State		Ultimate Limit State	
	Z_{Crack} (m)	Surcharge (kPa)	Surcharge (kPa)	Additional surcharge (kPa)
6R8-2	0.15	6.85	9.45	2.60
9R8-3	0.12	7.17	10.76	3.59
12R8-4	Not Applicable	Not Applicable	4.40	Not Applicable
14R12-2	0.15	7.50	23.15	15.65
17R12-3	0.12	6.85	23.48	16.63
21R12-4	0.18	11.41	21.52	10.11

Table 3- Main properties considered in the application of the expeditious method (for all the 6 walls).

<table>
<tr><th colspan="2">Face of the wall</th><th colspan="2">Backfill</th><th colspan="2">Reinforcement</th></tr>
<tr><td>γ' (kN/m^3)</td><td>24</td><td>γ' (kN/m^3)</td><td>16.30</td><td>Thickness (mm)</td><td>0.30</td></tr>
<tr><td>Thickness (mm)</td><td>20.50</td><td>ϕ' (º)</td><td>40</td><td rowspan="2">Area/m wide (m^2)</td><td rowspan="2">0.0003</td></tr>
<tr><td>Area/m wide (m^2)</td><td>0.02</td><td rowspan="2">K_0</td><td rowspan="2">0.36</td></tr>
<tr><td>I (m^4)</td><td>7.18E-07</td><td rowspan="3">$T_{máx}$ (kN/m)</td><td rowspan="3">1.40</td></tr>
<tr><td>E (MPa)</td><td>50</td><td rowspan="2">K_a</td><td rowspan="2">0.22</td></tr>
<tr><td>σt (kPa)</td><td>30</td></tr>
</table>

Table 4- Main properties considered in the application of the expeditious method (different for each one of the 6 walls).

Reinforcement	Walls					
	6R8-2	9R8-3	12R8-4	14R12-2	17R12-3	21R12-4
Deformability modulus of the 1st reinforcement from the top (kPa)	7 000	10 000	7 200	18 000	26 000	20 000
Deformability modulus of the other reinforcement elements (kPa)	8 600	11 600	8 800	19 600	27 600	21 600

5 RESULTS

Figures 5 and 6 show the horizontal face deformation measured along the height of the wall on some of the walls tested by Pinto (1992). These figures show also the corresponding deformation calculated by the expeditious method (OSSAD (Geo Var)), generally for two levels of surcharge: before and after the wall has reached the SLS. Furthermore, these figures show the results where it was not considered the confinement or the embedment length of the reinforcing elements (OSSAD (K0). A consistent and valid methodology for the different walls have been developed, where the effects (confinement and embedment) are indirectly incorporated into the calculation. Thus, the results become significantly closer to the laboratory measurements for any level of surcharge.

Very similar values were observed between laboratory results and the expeditious method (OSSAD (Geo Var)), for all the surcharge levels, for all types walls studied. The similarity is even better for the highest levels of surcharge. The results obtained show clearly that the expedition method can indeed predict the horizontal face deformation of brick retaining walls reinforced with geosynthetics, despite the fact that the method is based on a very simple structural scheme and it is of very simple implementation.

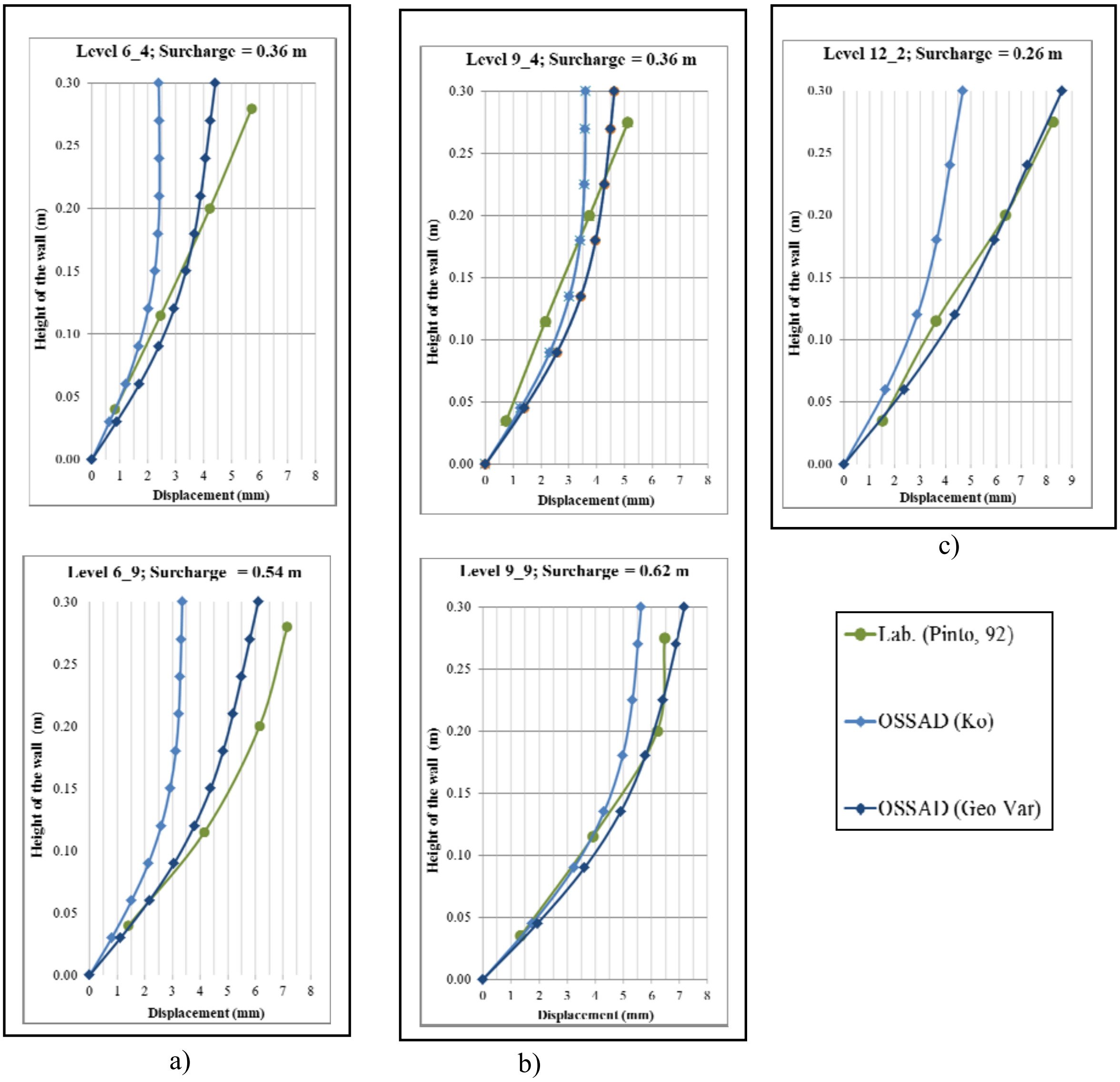


Figure 5 – Horizontal face deformation for two levels of surcharge (prior and after SLS) for the walls: a) 6R8-2, b) 9R8-3 and c) 12R8-4.

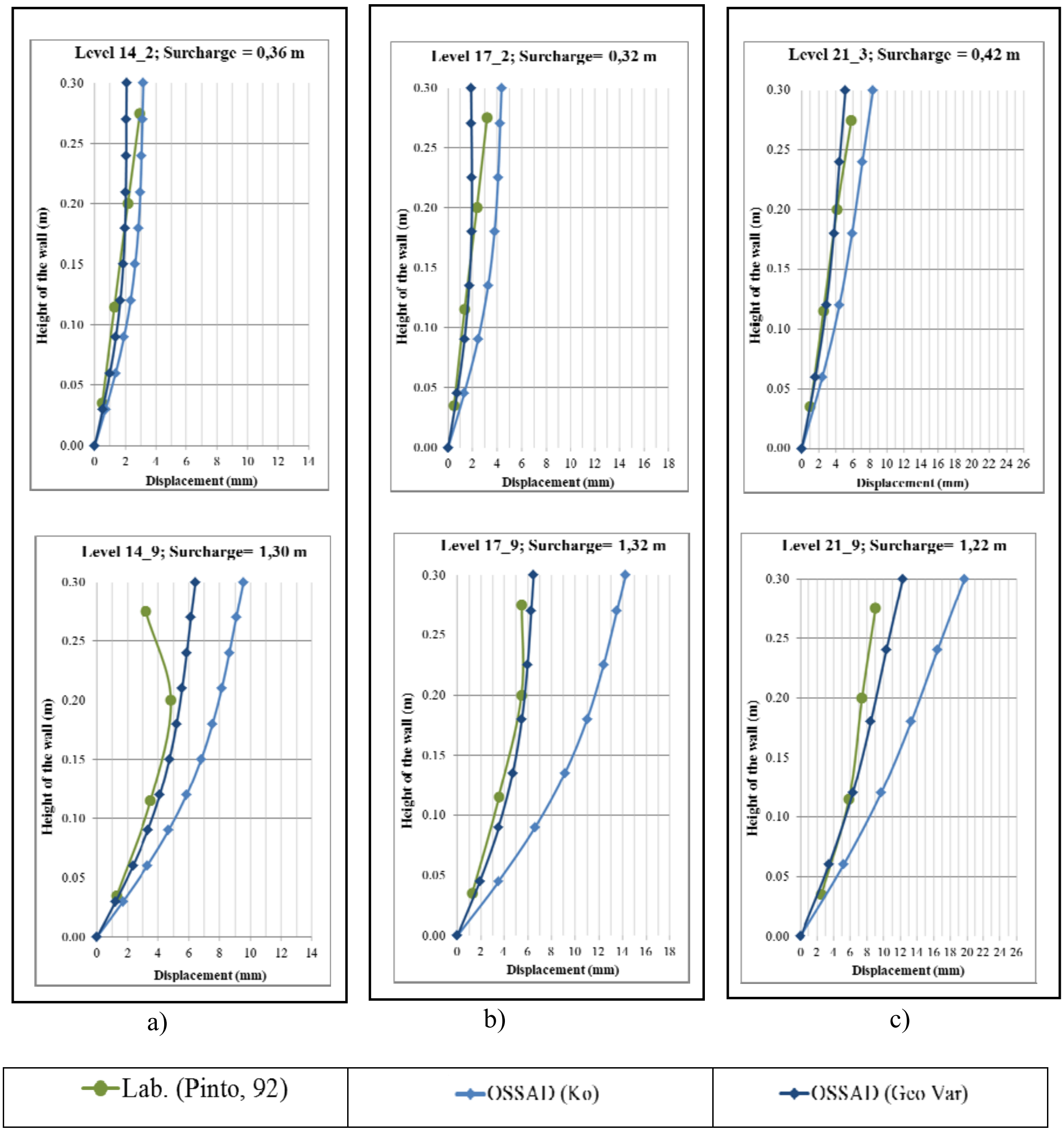


Figure 6 – Horizontal face deformation for two levels of surcharge (prior and after SLS) for the walls: a) 14R12-2, b) 17R12-3 e c) 21R12-4.

6 CONCLUSIONS

The expeditious method proposed by Correia (2003) proved to be a valid and simple alternative for predicting the face deformation of brick masonry walls reinforced with geosynthetics. The main conclusions to be drawn from this study are:

- In the brick retaining walls reinforced with 80 or 120 mm long geotextile sheets, the deformation obtained by the expeditious method becomes, in general, closer to that measured in the laboratory tests, as the level of surcharge increases. However, the initial difference is not significant and that can be due to the reduced confinement effect of the reinforcing elements for those surcharge levels;

- The walls reinforced with geosynthetics 120mm long supported more load, and do not reached the collapse stage. However, with the application of the expeditious method it is not possible to predict effects as the pull-out of the geosynthetics, verified by Pinto (1992) in some of these walls;

- The expeditious method requires some additional considerations to be developed in the future as it does not account directly effects such as confinement or the length of embedment of the reinforcing elements. However, a consistent and valid methodology was achieved for those walls under study, whereby these two effects were indirectly incorporated in the expeditious method. This consideration made the results get closer to the laboratory measurements for any level of surcharge.

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