Reinforced walls - Effect of the distance between reinforcements on reduced models

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ABSTRACT: Evaluate the influence of the relationship between the reinforcement stiffness and the soil stiffness on the behavior of soil structures reinforced with geosynthetics can contribute to a better comprehension of the structure mechanisms. Finite Element analysis of physical models could represent a valuable tool to better understand some of the effects acting in these structures. The behavior observed in tests conducted on physical reduced models representing a reinforced wall submitted to a loading applied trough a footing on the top of the structure, are compared to results of finite element analysis of this structure. The physical reduced models use reinforcement materials able to represent real reinforcements, chosen from the ∏ Buckingham Theorem considerations, and vary the spacing between reinforced layers. The structures were analyzed using the finite element software PLAXIS. This work presents the analyses of three models: one reinforced material with three different spacing between layers. As presented in the results, it is possible to observe that a change on the soil reinforcement spacing meant an increase on the soil elasticity modulus, hence, increasing the confining stresses on the reinforced layer. As greater, the soil elasticity modulus, more significant is the gain on the confinement (iteration effect).

Keywords: Geosynthetics, Reinforcement; Layer thickness; Rigidity; Finite Element Method

1 INTRODUCTION

It is important to know the behavior of soil reinforced structures in order to obtain optimized projects. Therefore, discussions regarding the iteration soil-reinforcement became recurrent, due the fact that the comprehension of the structure behavior is fundamental. Many authors have been researching the reinforcement stiffness influence in structures of reinforced soil, using numerical models as well as physical models (Allen et al 2003, Bathurst et al 2008; Bathurst et al 2009; Yang et al 2012; Ehrlich et al 2012).

The stress transferring and restrictions on lateral deformations characterize the soil-reinforcement iteration mechanism. Taking an initial proposal of Jones (1985, apud Oliveira 2006) the effect of the reinforcement stiffness might be presented as an element which is submitted to a vertical compression defined as σ_v and a horizontal tension σ_h which is the parameter to be determined in order to define the element state of tensions. In accordance to the soil classical mechanics, it is kwon that the horizontal stress is a function of the lateral soil displacement (Oliveira 2006).

Evaluate the influence between the reinforcement stiffness and soil stiffness on the behavior of soil reinforcement structures can contribute to a better comprehension of the mechanisms involved. The interpretation through finite element models of reduced models can represent a tool capable to help on this matter.

Gomes (1993) realized a batch of tests on reduced models varying the stiffness of the reinforced materials as well as the spacing between reinforced layers, submitting the structures to a loading applied trough a footing. The author presented, besides the reinforcement properties adopted, the curves loading-footing displacement and the face displacement. The application of reinforcement of different stiffness imply a significant variation on the structure deformation behavior.

The present work presents a partial analysis of Gomes (1993) results applying finite element simulation.

2 REDUCE MODELS TEST

Soils structures in reduced models and the numerical modeling are some methods applied to acquire knowledge regarding the behavior of reinforced structures. Reduced model works are usual on academic researches; nevertheless, it is necessary to be careful with the materials applied because those also need to represent the proportional reduction to the reduction size.

The set of experiments using reduced models realized by Gomes (1993) is one of the most complete works in the literature and one of the few that aim to comprehend the reinforcement stiffness influence. The author constructed, in reduced size, models of typical wall structures, as shown in Figure, using different materials. The research objective was to evaluate the wedge behavior with the reinforced stiffness variation. The models were taken to the rupture using imposed solicitations applied by the action of an overload transmitted through a footing, with variable distances from the wallboards.

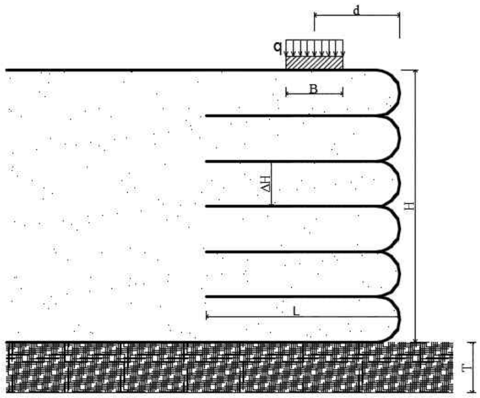

Figure 1. Physical modeling scheme of a structure of typical reinforced soil (Modified from GOMES 1993).

In order to represent a real size wall the reduced model used by Gomes (1993) was defined based on the ∏ Buckingham Theorem of the dimensional analysis. The ∏ Buckingham Theorem is a central theorem on the dimensional analysis, making it possible to define the important non-dimensional groups for the problem and to predict the functional relation among them. In order to do so, it is necessary to characterize all the problem variables, as shown in Equation 1:

$$q = f_1\left(H, \Delta H, L, \gamma, \phi, E_s, R_t, E_r, f, \gamma_f, \phi_f, E_f, T, d, B, w, t\right) \tag{1}$$

where q = surcharge load at the soil surface, H = height of wall, ΔH = layer thickness , L = reinforcement length, γ = unit weight of the backfill soil, φ = friction angle of the backfill soil, E_s = backfill soil elasticity modulus, R_t = tension resistance, E_r = tangent stiffness, f = interface shear angle between reinforced and backfill soil, γ_f = unit weight of the foundation soil, φ_f = friction angle of the foundation soil, E_f = Young's modulus of the foundation soil, T = thickness of the foundation soil, d = horizontal distance of center surcharge load is away from wall, B = width of the footing, w = footing displacement, t = thickness of reinforcement

Taking L (length) and F (force) as fundamental dimensions, the problem of a reinforced structure on the stiffened foundation can be expressed by a relation involving 10 non-dimensional terms and independent among them, Equation 2

$$\frac{qB}{R_t} = F_1\left(\frac{H}{\Delta H}, \frac{L}{\Delta H}, \frac{d}{\Delta H}, \frac{B}{\Delta H}, \frac{t}{\Delta H}, \frac{w}{B}, f, \phi, \frac{\gamma \Delta H^2}{R_t}, \frac{E_r}{E_s}\right) \tag{2}$$

The equality conditions imply on the equality of each non-dimensional terms of the model to the $\prod_1$ corresponding terms of the prototype. Gomes (1993) used those equations to define the adequate materials and dimensions.

The soil material used was a medium sand, clean and uniform, thrown on the box by manual dispersion, through the technic of "sand rain", aiming to obtain uniform sample. The parameters used to characterize the soil are described on Table 1.

Table 1. Soil parameters (medium sand).

γ_{nat} unit weight of the soil [kN/m³]	γ_{sat} unit weight of the saturated soil [kN/m³]	$\nu(nu)$ Poisson's ratio	c cohesion [kN/m²]	$\phi(phi)$ Friction angle [deg]	n porosity [%]	G Specific gravity mass
16	20.2	0.3	1	42	37,5	2,63

The reinforcement material analyzed was a plastic film, tested on the transversal direction. The reinforced material used on the analysis is described on Table 2.

Table 2. Physical and mechanicals properties of the material used as reinforced elements on the reduced models.

Nominal thickness [mm]	Mass per area unit [g/m²]	Tension resistance [kN/m]	Maximum load stretching[%]	Tangent stiffness [kN/m]
0.20	75	0.55	80	5.5

Figure 2 illustrates the behavior of the reinforced element during wide-width tensile tests.

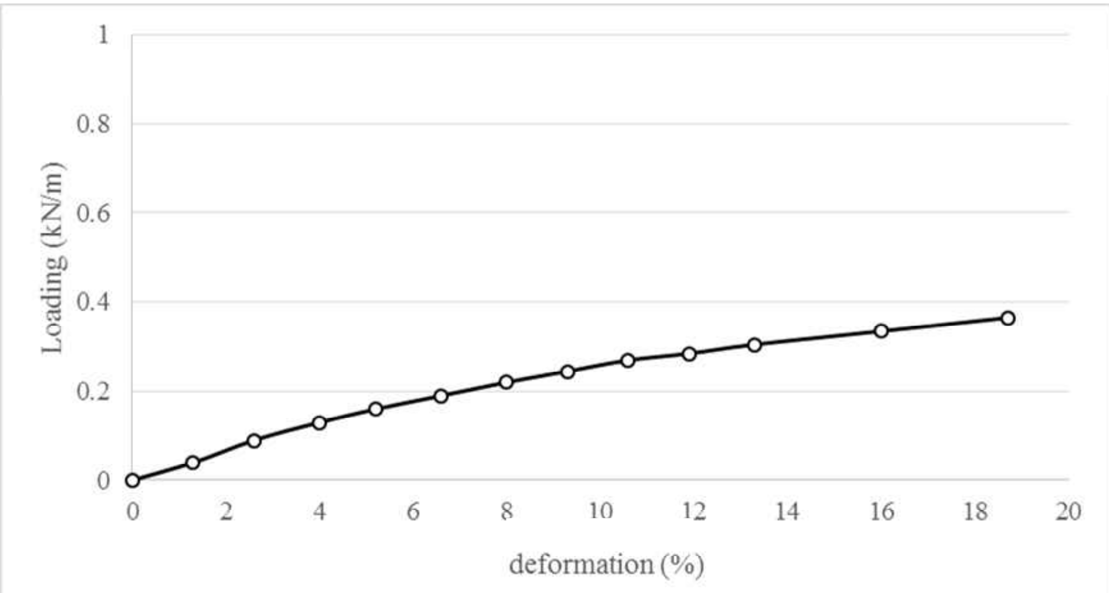

Figure 2. Load-deformation curve for the material used as reinforcement element on the models (Modified from GOMES 1993)

3 FINITE ELEMENT ANALYSIS

3.1 *Adopted model*

The analysis of the physical models results presented by GOMES (1993) were realized using the finite element software PLAXIS. This work presents the analysis performed for three models, being each of them with different spacing between reinforced layers.

The structure analyzed has a total height of 240 mm, spacing between layers of 30 mm, 40 mm and 60 mm, reinforcement length of 150 mm and the loading is realized through a footing of 50 mm which has its center located at a distance of 55 mm, in relation to the reinforced face structure. The structure geometry is presented in Figure 3.

Figure 3. PLAXIS model example of a reinforced soil structure modeled.

The adopted Mohr Coulomb constitutive model considers Gomes (1993) parameters presented in Table 1, but the soil deformation modulus needs to be estimated because the author did not evaluate this parameter. Moreover, Queiroz et al (2006) evaluated the application of this constitutive model for similar results presented by Gomes (1993) and concluded that the model is suitable.

In order to estimate this elasticity modulus, it was applied the $\prod$ theorem that indicated an order of magnitude around 1000 kN/m² to represent a sand in reduced model. This value demonstrated to be excessive when applied on the analysis, so the value was gradually and manually reduced.

In order to evaluate the footing load vs. displacement curves and the face horizontal displacement of the reinforced structure at a height of 0.58 h vs. the footing displacement obtained by finite element method are compared against the results presented by Gomes (1993).

3.2 *Spacing variation*

The analysis results refer to a reinforced soil structure that contains the soil described in Table 1, and the material used for reinforcement described in Table 2. The spacing between reinforced layers for the analysis were 30 mm (with 8 layers), 40 mm (with 6 layers) and 60 mm (with 4 layers).

Figure 4 presents the results of footing load vs displacement curves, when the spacing between layers is 30 mm, for distinct values of soil elasticity modulus (400 kN/m², 500 kN/m² and 600 kN/m²). The results for each elasticity modulus were compared with the results obtained from the physical analysis presented by Gomes (1993).

During the footing displacement, from 0 mm to 5 mm, the best-fit curve, compared to the physical model presented by Gomes (1993), is the curve that corresponds to an elasticity modulus equal to 400 kN/m². On the other hand, from 5 mm up to 6 mm the best-fit curve is reached considering a modulus of 500 kN/m² and from 6 mm up to 12 mm, a modulus of 600 kN/m².

The face displacements of the reinforced structure present a good correlation against the results presented by Gomes (1993) up to 5 mm of footing displacement (see Figure 4-b). From 5 mm up to 9 mm the results obtained from numerical analysis presented a smaller face displacement when compared against the author's test curves. Between 9 mm and 12 mm the curves presented a better shape when compared with the physical results.

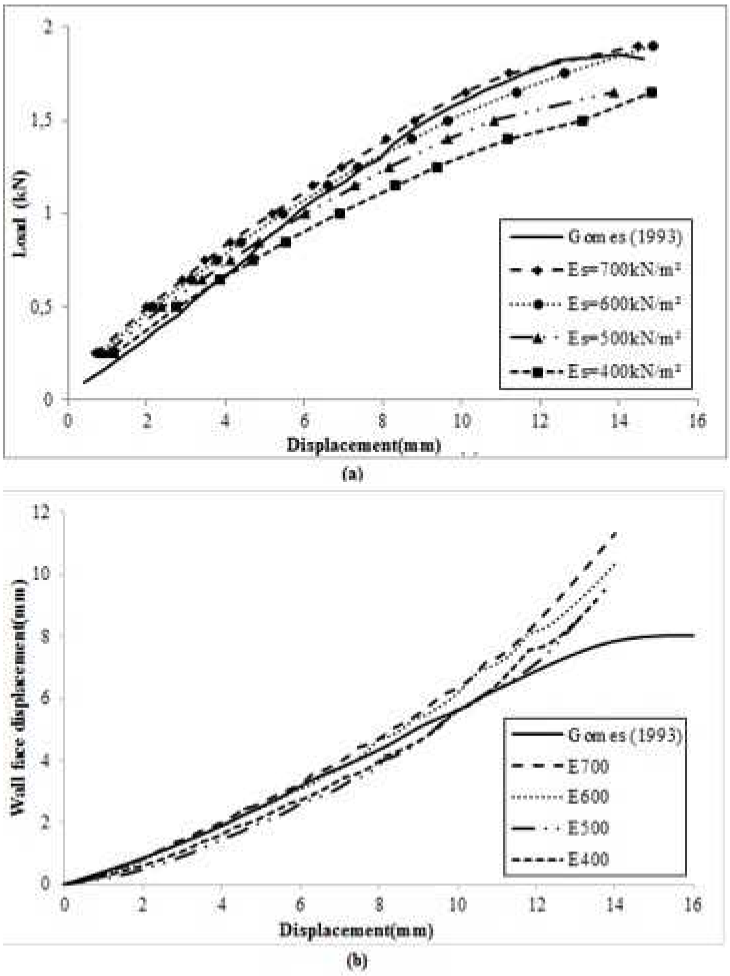

Figure 4. Gomes (1993) and finite element results for analysis considering spacing between layers equal to 30 mm: (a) Relation between the applied loads and footing settlement, (b) Relation between face horizontal displacements of the wall vs footing settlement.

Considering a 40 mm spacing between reinforced layers, three distinct soil elasticity modulus: Es = 400 kN/m², Es = 500 kN/m² and Es = 600 kN/m², were applied. Those elasticity modulus present suitable results when compared with the results obtained by Gomes (1993).

Figure 5-a presents the results for footing loads vs footing displacements for different values of soil elasticity modulus as well as the physical analysis results performed by Gomes (1993).

For a footing displacement varying from 0 mm up to 4 mm the best fit with the physical results is reached with an elasticity modulus of 400 kN/m², however as the loading is increased and the footing displacement varies between 4 mm and 9 mm, the best fit is reached with an elasticity modulus equivalent to 500 kN/m².

In order to evaluate the face displacement of the reinforced soil structure, face displacement curves at 0.58 h vs footing displacement for three distinct elasticity modulus were generated and compared against the physical model results. A minimum variation between them is observed up to a face displacement of 4 mm, as can see at Figure 5-b. From a footing displacement of 4 mm up to 7 mm the soil elasticity modulus that best fit the results presented by Gomes (1993) was equal to Es = 600 kN/m².

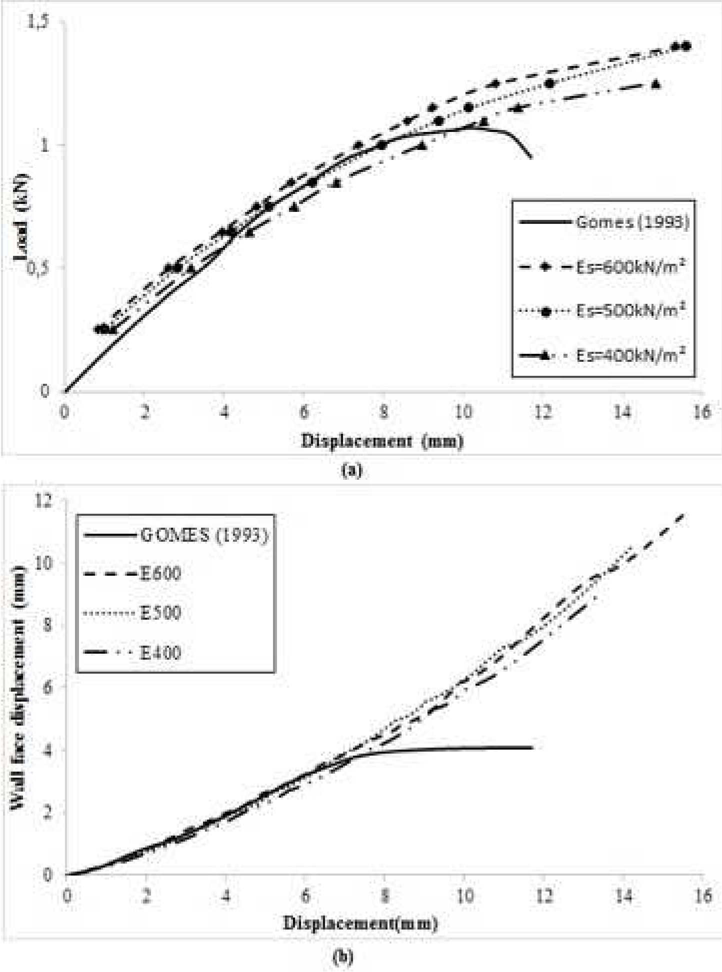

Figure 5. Gomes (1993) and finite element results for analysis considering spacing between layers of 40 mm (a) Footing load vs displacement curves. (b) Relation between face horizontal displacements of the wall vs footing displacement.

The last analysis using the reinforcement is performed considering a spacing between layers equal to 60 mm. For this analysis three different soil elasticity modulus were used: Es = 110 kN/m, Es = 200 kN/m and Es = 600 kN/m.

The load vs footing displacement curves for the different values of soil elasticity modulus obtained by finite element analysis, see Figure 6-a, fits best the results obtained by Gomes (1993), on the interval of 0 mm to 3.3 mm, with an elasticity modulus equal to Es = 200 kN/m². As the load is increased, for the footing displacement varying from 6.5 mm up to 9.5 mm, the elasticity modulus that best fits the physical models is equal to Es = 110 kN/m².

Figure 6-b presents face displacement curves at 0.58 h vs footing displacement for the three different soil elasticity modulus as well as the results presented by Gomes (1993). One might notice the finite element curves presents smaller face displacement up to a defined footing displacement point. For instance, the E600 curve presents, up to a footing displacement of 9.5 mm, a smaller face displacement than the values presented by the physical model of Gomes (1993), nevertheless from a 12 mm footing displacement the curves inverses one against other, resulting a greater end face displacement on the finite element analysis against the author's results.

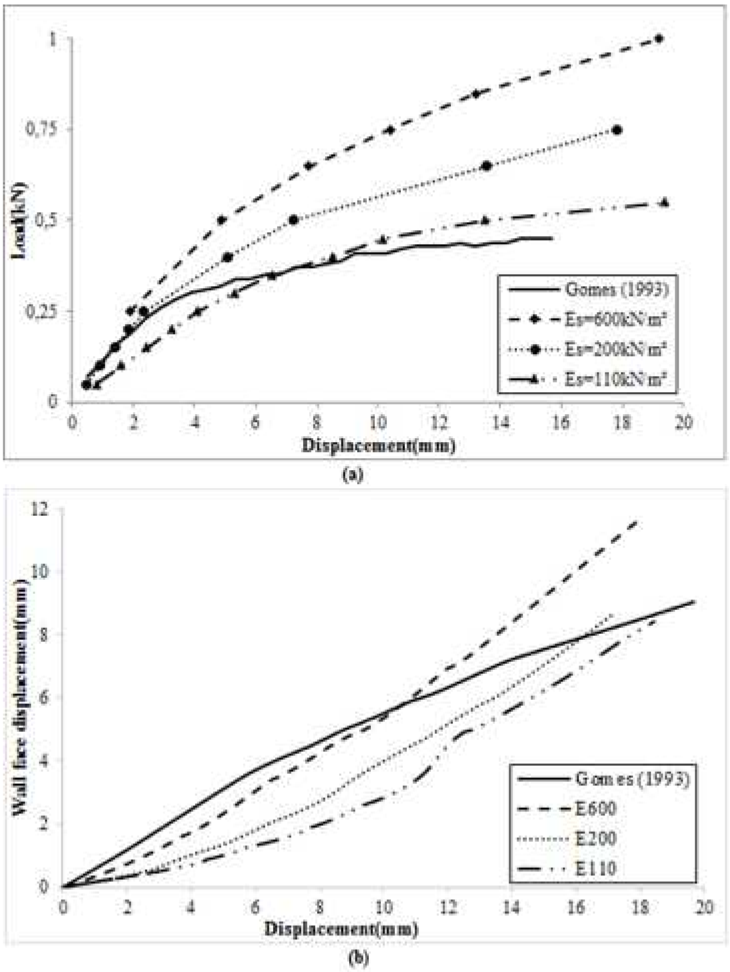

Figure 6. Gomes (1993) and finite element results for analysis considering spacing between layers of 60 mm (a) Footing load vs displacement curves. (b) Relation between face horizontal displacements of the wall vs footing displacement.

4 RESULTS DISCUSSION

The finite element model used in this work could not represent the rupture condition; however, it was capable of representing the physical model results, presented by Gomes (1993), satisfactorily under service conditions, object of study of this work.

The application by Gomes (1993) of the $\prod$ Buckingham theorem on the dimensional analysis demonstrated to be valuable, especially because its utilization helped to define which materials should be chosen in the reduced models. Hence, it has been chosen materials that presented tensile resistance and elasticity modulus compatible with the reduced model. Nonetheless, the theorem application for soil models demonstrated some difficulties, mainly because the soil elasticity modulus varies with the confining stress, as it has been illustrated on the load-displacement curves, where the elasticity modulus increases as the loading and the footing displacement are increased. Another constitutive model could be chosen for this analysis, as for example a model that represents the resistance gain of the soil as the loads were applied. However, the authors preferred to perform repeated analyzes by varying the modulus of soil elasticity manually using the Mohr Coulomb model, a model that has already been consolidated and presents excellent results when dealing with the software used in this analysis.

Reduced models analysis using finite element might be a significant contribution to evaluate the behavior of reinforced soil structures. It is important to point that the material used on models with small dimensions ought to be evaluated, once that those also need to represent this reduction.

On the results presented, it is possible to observe that a reduction on the soil reinforcement spacing meant an increase on the soil elasticity modulus. Hence, increasing the confining stresses on the reinforced layer.

Major soil elasticity modulus indicates increasing of the soil confinement provided by the reinforcement. The results indicates that this phenomenon is directly affected by distance between reinforcements, as expected. The main importance this kind of analysis is to better understand the relevance of the confinement effect and to stimulate new researches that could conduct to design procedures able to consider the advantages of reduce the distance between the reinforcement layers.

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