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Numerical tools for geosynthetic reinforced walls design: A performance assessment on the basis of laboratory-scale models results

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ABSTRACT: Many works in literature on the basis of field measurements and laboratory models have shown that reinforcement extensibility has great influence on deformation and failure of geosynthetic reinforced walls. Bearing in mind the successful application of Finite Element Programs in geotechnical analyses, especially in soil structures stability analysis, the aim of the present paper is to bring some insight about the ability of these programs in adequately address displacements and deformation on geosynthetic reinforced walls, considering the particular strain-stress distribution along reinforcement length for different geosynthetic stiffness. Although computational resources based on FEM have been found to be highly effective tools, the constitutive models available in these programs are not always able to reproduce the main features of this behaviour, probably providing inconsistent results. Still, it is important to keep in mind that all constitutive models have limitations which sometimes are not easy to readily be recognized by programs users. In order to contribute to this topic little discussed in literature, this work presents some numerical simulations that were modeled considering the same pattern of the experimental small-scale models. Comparing results, the studies here presented suggest that numerical analyses using the selected program are able to reproduce the load-displacement trend for reinforced wall structures but they not accurately describe some phenomena as yielding, strain softening and post-failure behaviour. Still comparing results, this work emphasize that to comprehend the behaviour of geosynthetic reinforced walls in all the variety of geomaterials available and contexts it is necessary to have a robust mechanical framework that are able to describe the complex interaction between soil-geosynthetic.

1 INTRODUCTION

Spurred by the successful application of polymer reinforcement materials on retaining walls construction, a more fundamental understanding of geosynthetics behaviour for this application has been developed. One aspect that merits special attention is the critical influence of load-elongation properties on reinforcement behaviour.

Generally speaking, the stability of a geosynthetic reinforced structure is conditioned by soil-geosynthetic interaction, which induces an overall redistribution of stress-strain fields in the terrain. These interaction mechanisms depend on material's properties like tensile strength and stiffness, reinforcement spacing and bond length, and features like confinement stresses and applied surcharge loads.

Results presented by some experimental studies like Gomes (1993) in which laboratory-scale models of geosynthetic reinforced walls were performed, not only suggest that the modulus of the reinforcement has a great significance since it governs the force that can be mobilized, but mainly show that failure mechanism developed broadly depends on the reinforcement load-extension characteristics.

During the last decades, significant advances have been made regarding the use of Finite Element Programs in geotechnical analyses, especially in soil structures stability analysis. It may be noted that there is a wide variation of properties for any material and polymer type, and is important forecasting different behaviours associated to different geosynthetic stiffness and extensibility.

The numerical and theoretical study reported in this paper was undertaken to evaluate the response of some of the most employed constitutive models to geosynthetic reinforced structure simulation.

To achieve this objective, some results obtained by Gomes (1993) with laboratory-scale models of geosynthetic reinforced walls were compared to numeric predictions considering the same pattern of the experimental tests.

The numerical program selected to carry these analysis was PLAXIS (Finite Element Code for Soil and Rock Analyses), Version 7.2. The primary consideration for this choice resides in the fact that this program presents special functions that allows geosynthetic reinforcement modeling and specific constitutive models for geomaterials. Moreover, this program is widely spread in geothecnical media.

2 EXPERIMENTAL RESULTS (GOMES, 1993)

The results obtained by Gomes (1993) with laboratory scale models provided a set of basic pattern of displacements and failure behaviour for geosynthetic reinforced structures.

In highly extensible reinforcements (represented in the scale models as non-woven geotextile, plastic sheets and PVC film), an excessive deformation of the soil reinforced mass was observed without a well defined shear surface. Still in these cases, the results are greatly influenced by the bond mechanism (interaction between soil and reinforcement).

For reinforcements with low stiffness and small strain at failure (represented by cork sheet in the scale models) the collapse was caused by soil mass puncture under local stress concentrations caused by a previous rupture of reinforcement.

Lastly, for stiff reinforcements (paper, rough and smooth aluminum sheets) a defined shear surface was clearly observed as well as a better stress-strain response. Further, the concept of limit equilibrium is more suitable for this case, as Gomes (1993) has already pointed out. Still, the data have suggested that boundary conditions do not affect measurements in contrast to extensible materials.

3 NUMERICAL ANALYSES

3.1 *General characteristics*

Numerical analyses were performed in attempt to reproduce some of laboratory-scale models previously described (strictly speaking, the “series I” described in Gomes 1993). Concerning characteristics of the problem, it was used a plane strain model with 6-nodes triangular elements. Figure 1 presents the model layout for numerical analysis and Figure 2 the mesh used in the analyses.

3.2 *Soil modeling*

The first steep on soil modeling consisted on the constitutive model selection. In fact this steep was the most time consuming on the analysis and demanded and additional theoretical study. It consisted on a carefully review about the intent and background of any constitutive model available on software before adopting it to be sure that it is the most compatible with the specific model conditions.

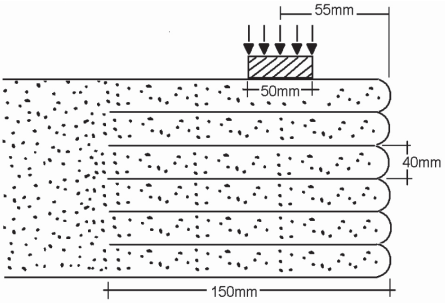

Figure 1. Model layout for numerical analysis.

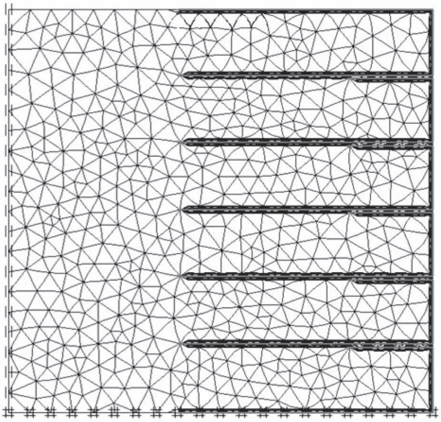

Figure 2. Plane strain finite element mesh of the geometry.

In any stability evaluation it would be desirable that the analysis could provide accurate results about displacements on failure and post-failure. Considering that one of the major problems on FEM analyses is to obtain reliable results on large displacements, the collapse analyses of soft soils foundations, for instance, are hard to be successful. Unfortunately, the current constitutive models and the usual programs based on FEM are just able to provide a range of values without any accuracy. One way that relatively enables to deal with this problem is to conduct the analyses on steeps and spatially update the date on the basis of the previous steep results in each one of these phases.

Still, an ideally model for the type of the soil and the conditions established should be able to consider the collapse by the lost of resistence phenomenon called yielding. Normally, this kind of rupture has “shear bands” formation. In this case, many ways of rupture may happen, and many of these have the same critical load. However, none of the current constitutive models implemented on commercial numerical programs enables to consider this phenomenon.

Considering all the limitations of the models available on the selected program and keeping in mind what an adequate model should considered, the alternative chosen was to model the soil as elastic-perfectly plastic material, with Mohr-Coulomb failure surface. This selection has been made due to parameters required (they are easy to be obtained) and mainly because it is implemented with reliability in the most of programs. As any model, the Mohr-Coulomb Model has some limitations: the elastic modulus is not a function of confinement stresses; the dilation angle is considered as a constant, hence independent of the historical of the displacement. Still, as all models available on the program selected, this model can not reproduce with accuracy large deformations.

Table 1 furnishes soil properties used in numerical analyses. Cohesion and friction angle were obtained from reinterpretation of direct shear tests results presented by Gomes (1993). Dilation angle was also estimated from data provided by Gomes (1993), see Figure 3.

Table 1. Mechanical Properties of soil employed in the analyses.

Soil Parameter	Name	Value	Unit
Material model	Mohr-Coulomb	–	–
Soil weight	γ	16	kN/m^3
Young's modulus	E	3300	kN/m^2
Poisson's ratio	ν	0.3	–
Cohesion (const)	c	2.94	kN/m^2
Friction angle	ϕ	37.47	–
Dilation angle	ψ	12	–

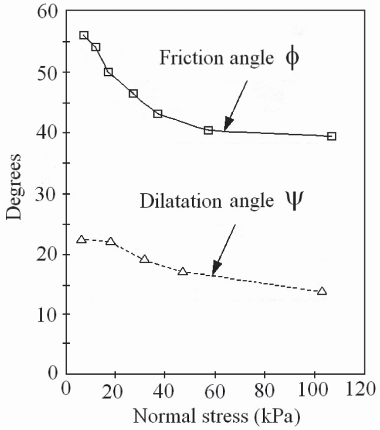

Figure 3. Sand friction and dilation angles versus normal stress (Gomes, 1993).

According to Lambe e Whitman (1969), the acquisition of this parameter in this way, generally result in errors limited in 2 degrees, being critical for dense sands, what doesn't happen in this study.

Young modulus was obtained by linear elastic analyses of the load-displacement curve of the scale model reinforced with aluminum sheet.

It should be noted that the direct shear tests and the small-scale models were performed with relative lower confinement stresses (about 100 kPa), and the soil was a silty sand with angular grains. Regarding all of these aspects, the estimation resulted in a low value of the elastic modulus and high friction and dilatation angles.

3.3 *Reinforcement modeling*

The available linear element in chosen software to reinforcement modeling does not posses bending stiffness, like a beam element with null inertia and null compressive strength. However, the interface elements enable reinforcement displacement in relation to soil mass. Parameters like strength and stiffness attributed to these interface elements are governed by a soil constitutive model, by a multiplying factor of the constitutive strength (called interface strength) and by an equivalent thickness. Overall analyses described in this paper have as interface thickness the minimum value allowed by the program (0.01 m).

To avoid the placement of two reinforcement layers in direct contact near the wall face, a soil layer with 2 mm was disposed between them. This strategy was taken due to the difficulty in modeling interface among reinforcement elements.

Table 2 furnishes normal reinforcement stiffness and interface strength of soil-reinforcement contact surface (provided by Gomes 1993).

Table 2. Mechanical Properties of the reinforcement employed in the analyses.

Type	Normal stiffness EA kN/m	Interface strength R_{inter} –
Plastic A	12.16	0.71
Plastic B/L	4.05	0.62
Aluminum	30	0.96

3.4 *Steps of analysis*

In order to avoid numerical instabilities, the surcharge load was applied by imposed vertical displacement, what enables the application of increasing loads even if the numerical model presents a large number of integration points under plastic state. As the currently model (Mohr-Coulomb) is not able in describing concepts of yielding and post-failure behaviour, the vertical displacement was imposed only until reaching the peak on the strength envelope forecasted on laboratory experiments.

Firstly, as displacements and inner tension caused by self weight were negligible, model construction were simulated as a single step process to avoid numerical instabilities. But, in agreement with the large deformations caused by load application, the simulation had to be divided in five steps of equal imposed displacements. We must point out that the software internally splits each step automatically, and uses a kind of Return Map Algorithm (Zienkiewicz, 2000) to calculate plastic deformations (Brinkgreve and Vermeer, 1998).

4 RESULTS OF NUMERICAL ANALYSES

Figure 4 presents results of both laboratory tests and numerical analyses in terms of loads as function of the imposed displacements applied in place of the surcharge load. The load is account like the sum of the nodal reactions where the displacements were imposed. It can be thought that such results are encouraging, in spite of the simple constitutive model used in analysis.

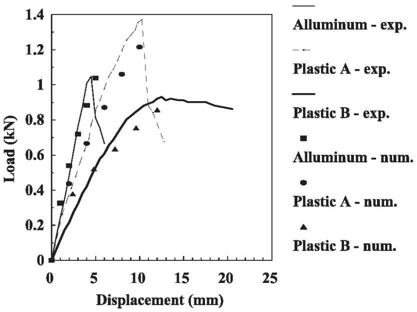

Figure 4. Comparisons between Numerical and Experimental Results in terms of loads and displacements.

Regardless, some interesting aspects must be pointed out on the basis of numerical simulations presented:

- The numerical model employed accomplished in represent both magnitudes and loading rate trends as imposed displacements functions in the vicinity of the peak loads recorded in the laboratory-scale models.
- In the specific case of aluminum sheets, the numerical results agree to the ones obtained by laboratory tests to the small deformations.

It is important to highlight that the results from tests with aluminum sheet reinforcement were used in the back-analysis of the soil Young modulus. The closeness of all numerical results to the experimental curve obtained with aluminum sheets (for small loads) suggests that the dependence of Young modulus on the confinement caused by reinforcement should not be overlooked in numerical analyses for displacement prediction in reinforced walls.

5 FINAL REMARKS

The purpose of this work was to assess the adequacy of finite elements predictions about performance of reinforced walls.

Numerical model results were compared to loads and displacements obtained by instrumentation of a laboratory small-scale model.

Regarding some limitations, it was only possible to model reinforcement as elastic material. Moreover, sand had to be considered elastic-perfectly plastic material (Mohr-Coulomb). Hence, the presented numerical analyses are not very accurate in describe some phenomena as yielding, strain softening and post-failure behaviour for reinforced wall structures.

Regardless, the studies here presented suggest the numerical analyses using PLAXIS are able to reproduce the load-displacement trend on geosynthetic reinforced walls, what is supported by the evidence from scale models from which numerical results presented minor deviations.

Future works in this field should take into account some important characteristics of geomaterials, like strain softening and relationship between soil deformability and confining stress. The authors suggest the employment of more sophisticated Critical State Models, like MIT-S1 (Pestana-Nascimento, 1994).

Still bearing in mind the geosynthetic reinforcement modeling, analysis showed that is prudent to take into account nonlinear stress-strain relationship of reinforcement materials, including its mechanical characteristics under confinement and creep.

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