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FINITE ELEMENT MODELLING OF THE DIRECT SHEAR TEST

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Abstract. The direct shear test was developed to obtain the failure envelope through a simple and direct analysis. It is one of the oldest and simplest tests for this purpose applied to soil analysis. However, during the direct shear test, the stress distribution in the sample is complex and not uniform. In order to improve the interpretation of the direct shear test results, the present work aims to study the stresses and strains in the sample during the execution of the direct shear test using a model based on finite elements (FEM). The Finite Element model was implemented in the software ABAQUS®, student version. The model is a two-dimensional representation of a section in the direction of the shear force. The shear is considered by applying displacements in a steady state analysis. For the material properties a Mohr-Coulomb elastoplastic model was considered. An evaluation of the chosen model was realised by a direct comparison of model results and laboratory tests, showing in general a good agreement. To evaluate the adherence between upper and lower plates to the soil specimens two geometric models were conceived: one considering toothed plates and another with smooth plates. It was found that the models were able to describe the typical stress and strain curves of the laboratory direct shear test when the results of shear are obtained from the fixed box reaction, although, with some discrepancies between the toothed plates and smooth plates models. The differences observed can be explained observing the failure zone which is distinct in the models: for the toothed plates model, the failure zone as expected, occurs in the central part of the model; as for the smooth plates model the failure zone falls out the central region. Differences can also be highlighted when the failure envelope is reinterpreted from the fixed box reaction, smooth plate models feature slightly smaller parameters, reinforcing the need for good plate crimping.

Keywords: direct shear, gripper plates, FEM.

1 Introduction

According to Head and Epps [1], the direct shear test is the oldest and simplest experiment developed to characterise the failure envelope of a soil sample. Despite relative simplicity, Pinto [2] states that the direct shear test shows a complex and non-uniform stress distribution within the specimen. Moreover, the rupture surface is formed by consecutively appearing plastification points [3] [4].

The failure surface, classically forced at the centre of the sample, may be displaced, constituting a wedge and coming out to the side of the sample, toward the gripper plate. As reported by Silva [5], this condition can be observed mainly at the stages of the direct shear test at low normal stresses and in stiffer soil samples.

It is recognized that in the recent years the direct shear test is losing spot to more complex and reliable tests, as triaxial. Although, in most soil mechanics laboratories the test is still routine due to its simplicity, quick execution and low cost. The current use justifies the need for good practice which in some cases is neglected. Is not hard to find in some labs that the test rate is set a constant for all soils evaluated. Porous stone and gripper plates quality or misuse can also be observed.

In this context, this work aims to realise numerical analyses using the finite element method (FEM) from a two dimensional model of the direct shear test. Two geometric models were used to analyse the stress and strain, aiming to verify the influence of the adherence between the gripper plates and the sample as well to understand the mechanism of rupture.

2 Previous studies

The numerical analyses of the direct shear test is not a new subject and a summarized review of applications can be found in Drescher [3], Dounias and Potts [6], Moayed et al. [7] and Salzar el al. [8].

The most adopted models for analysis are 2 and 3D Finite Element (e.g. Drescher [3], Potts et al. [4] and Moayed et al. [7]) and more recently the discrete element model (e.g. Dounias and Potts [6]; Salzar el al. [8], Bagherzadeh-Khalkhali and Mirghasemi [9]). A summary of the main observations is given in the paragraphs below.

Moayed et al. [7] performed a three-dimensional finite element modelling of the direct shear test. These authors obtained numerical models with good results compared to the laboratory results of sandy clays.

A two-dimensional analysis using the discrete element method was performed by Dounias and Potts [6]. These authors evaluated that plan analysis was sufficient; the possible three-dimensional effects would not significantly alter the results. In contrast, Salzar el al. [8] observed elements that moved outside the plane of possible two-dimensional analysis in three-dimensional analysis of the direct shear test using the discrete element method.

3 Methodology

Two characteristic geometric models were defined to verify the influence of the adhesion of the gripper plates to the sample: a geometric configuration with toothed plates and another with smooth plates.

Initially, results of the model with toothed plates were verified based on the observation of typical laboratory curves of direct shear test. After this verification, an analysis of adhesion the adhesion between the gripper plate and the sample was made by comparing the smooth plate model results and the toothed plate model results.

3.1 The FEM models

The choice of software for finite element modelling was based on license availability, usefulness and the quality of the obtained analyses. In this way, the ABAQUS® Student Edition software was chosen.

As reported by Dounias and Potts [6], the two-dimensional analysis of the direct shear test is sufficient for the understanding of stress and strains generated during the shear step. Thus the finite element models developed for this work are two-dimensional, in-plane strain. These models represent the central section of the sample, in the same direction of the shear force. The geometry of the model was based on real direct shear equipment. The soil sample was modelled with 2.00 cm length and 10.16 cm height.

In order to investigate the influence of the teeth of the gripped plates on the behaviour of the sample, two similar geometries were made, one with the smooth plates which is called in this work by smooth model (Fig. 1-a) and another with the teeth on the plate, in the present work called by toothed model (Fig. 1-b).

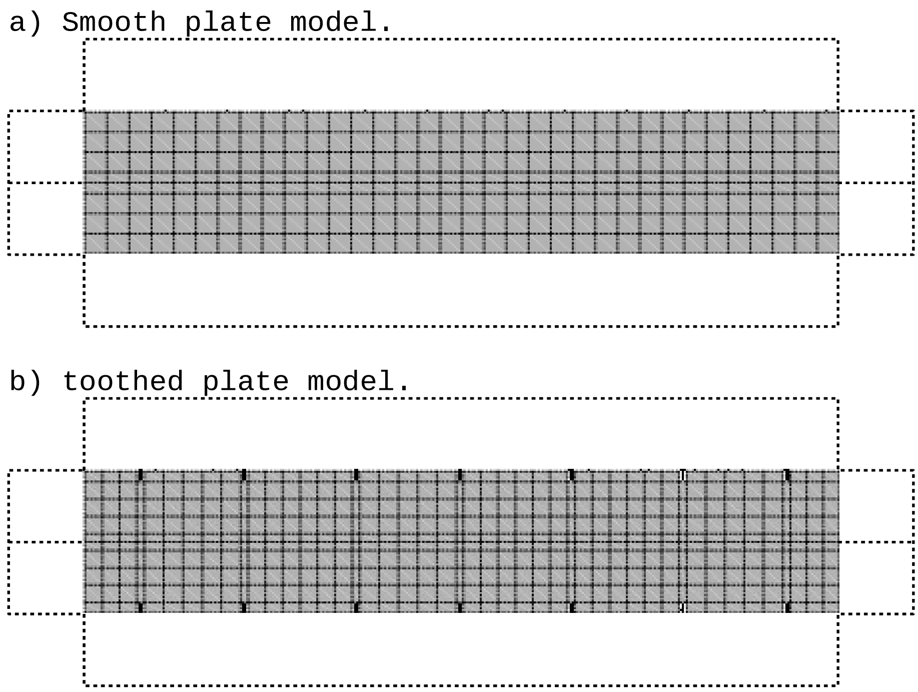

Figure 1. Geometries of the models

The models are compositions of parts representing the sample and parts representing the sides of the boxes and the gripper plates. The plates of the toothed model were modelled based on a real gripper plate (Fig. 2) and had seven rows of teeth, each tooth 0.15 cm high and 0.1 cm wide.

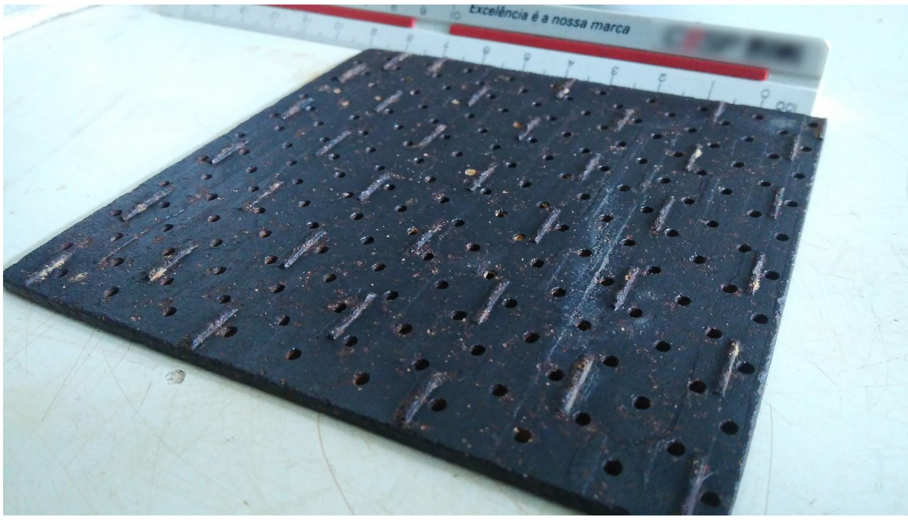

Figure 2. Real toothed plate

The parts used to represent the soil was modelled with a four-node bilinear displacement and pore pressure element (ABAQUS® element CPE4P). The part that represents the sample in the toothed model has 446 elements and in the smooth model 258 elements. The difference in the number of elements is mainly as a result of the modelling of the teeth, which restricted the construction of elements, increasing the number in the models with the toothed plate.

According to the test drainage premises (fully drained), the calculations are made in steady-state. Therefore, it is not possible to analyse the pore pressure excess, restricting the analysis to a drained behaviour.

An interaction between the metal parts and the soil was modelled considering an interface parameter, a surface friction coefficient, which relates the normal stress to the shear strength. A constant value of 0.3 was used for the simulations. This value is related with the tangent of the friction angle [10].

Three calculation steps were modelled for the simulations:

- The first, in this work called “geostatic”, has the purpose of giving the initial conditions to the model. In this step, 5 kPa of confining tension was applied, and the drainage conditions were defined.
- The second step, called “N application”, is used to apply the normal stress (N) to the upper plate, which transmits to the sample. Only vertical displacements are allowed in this phase, according to the restricting applied to metal parts representing the confining box. The box and the lower plate parts have a restriction of movement in the vertical and horizontal directions, besides the rotational restriction.
- In the last step, “shear step” (Fig. 3), the restriction of the upper half of the box was maintained and horizontal displacements are applied to the lower box and plate. To allowed vertical and rotational movement of the upper plate only a restriction of horizontal movement was applied to a single point, the bottom right vertex of the upper plate. This arrangement is intended to approximate the stress state of the model to that generated by the direct shear test, in which the normal stress is applied to the rigid plate and transferred to the sample, letting the rigid plate vertically move and rotate.

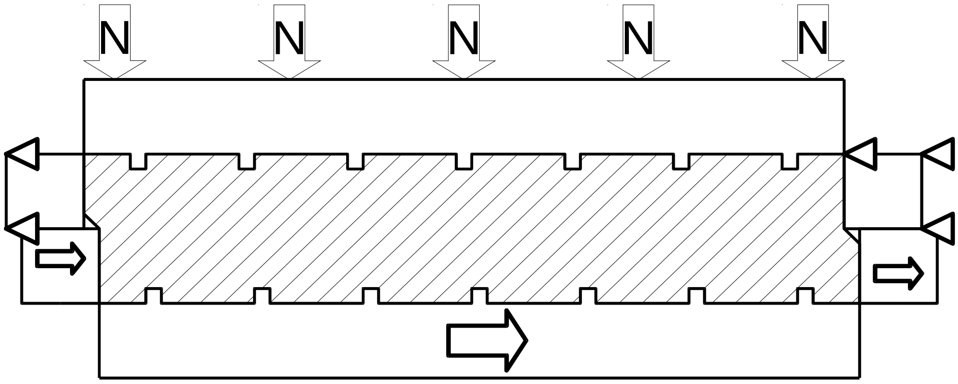

Figure 3. Requests and restrictions of the model in the shear step

During the shear step, the numerical results were saved in two ways: the measured stresses were saved along with the central elements of the sample and, the horizontal reactions of the upper half of the box were saved, similarly to the experimental measurements.

The parts representing the sample were modelled with an elastoplastic model with Mohr-Coulomb failure criterion. The parts used to represent the sides of the boxes, and the gripper plates (metal parts) were modelled as a rigid material.

In order to obtain the necessary parameters for modelling, metadata was searched in the bibliography. Godoi [11] performed several triaxial tests, direct shear tests and confined compression test for five sample points. These laboratory data were sufficient to obtain the friction angle (ϕ), cohesion (c) and elastic modulus (E). A constant reference value of 0.3 [12] was considered for the Poisson coefficient for all models and simulation.

4 Results and discussions

4.1 Preliminary analyses of the toothed plate model

In order to evaluate the applicability of the toothed model to analyse the direct shear test, the numerical shear strength development was compared to laboratory results obtained by Godoi [11]. In this evaluation, tree samples were used. The input parameters of the model are shown in Table 1. Parameters display in Table 1 are characteristic of a residual soil, and embraces a variation of friction angle from 27 to 30 degrees, cohesion from 18 to 47 kPa and elastic modulus from 3.7 to 5.7 MPa, parameters obtained from triaxial tests interpretation. Although, it would be more appropriate to use a non-residual and non-cohesive material to validate the model, these database was used due to data availability and also because Godoi [11] used the standard equipment which was used to define the basic geometry of the toothed model (Fig. 2).

Table 1. Modeling parameters for the evaluation

Sample	Cohesion (kPa)	Friction angle	E_{50} (MPa)
01	18	30º	5,7
02	45	29º	3,7
03	37	27º	4,5

The comparison between the numerical results and the experimental results of Godoi [11] are shown in Fig. 4, 5 and 6. The related figures display the relative movement of the box and the normalized shear strength (τ/N).

In a direct comparison between laboratory and numerical results from Fig. 4 to 6, it is noted that the numerical results characterise a stiffer material, which is expected as a constant elastic modulus E

was adopted.

Considering shear strength, samples 01 and 03, Fig. 4 and 6, show that the numerical model under predicts the shear strength behaviour, while in sample 02, Fig. 5, the model over predicts the developed strength. However, in general, it is possible to verify that the model is capable of characterising the typical behaviour of the stress strain curve of the direct shear test. It is important to highlight that this analysis is not a curve fitting procedure, but rather aims to characterize and generally compare typical curves obtained from the numerical model with average parameter (Table 1), with typical experimental curves.

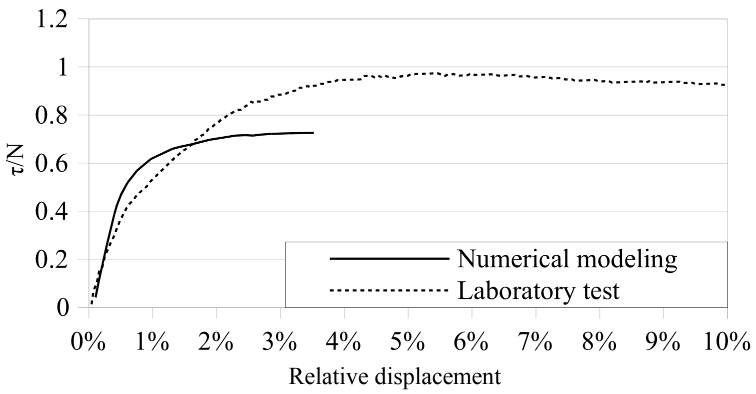

Figure 4. Evaluation of the model with Mohr-Coulomb envelope (sample 01)

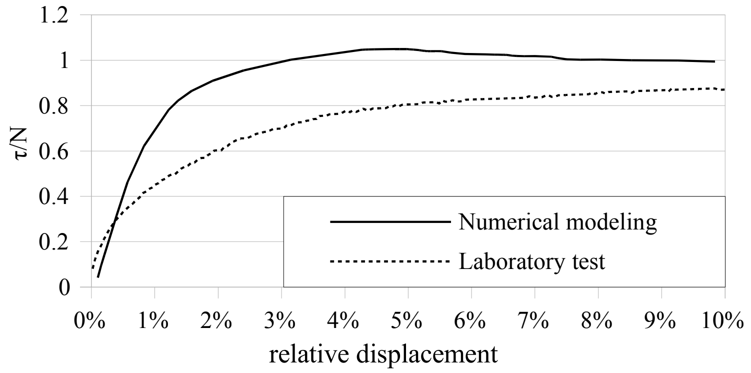

Figure 5. Evaluation of the model with Mohr-Coulomb envelope (sample 02)

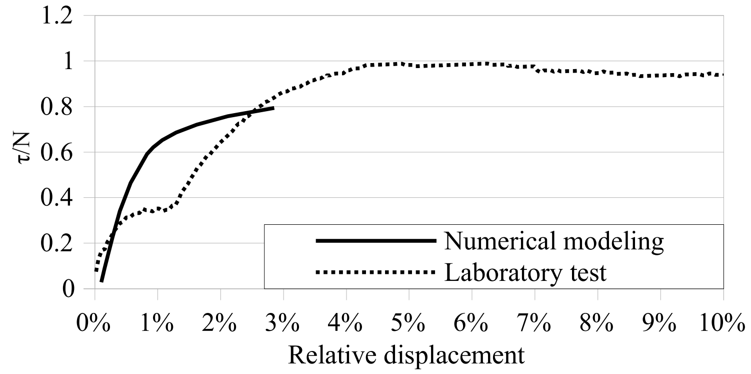

Figure 6. Evaluation of the model with Mohr-Coulomb envelope (sample 03)

4.2 The effect of adherence between the gripper plates and the soil sample

In order to evaluate the influence of the use of the gripper plate during the direct shear test, the results obtained with the toothed plate and with a model with a plain plate (smooth model) were compared. In these models, reference parameters were used (c = 20 kPa; ϕ = 20º and E = 3 Mpa).

Figure 7 represents the displacement versus shear strength curves of the smooth and toothed models. Strength in the figure are obtained from the fixed box reactions and also using the shear average from the central elements of the modelled samples.

From the Fig. 7 it is possible to note that the two measurements, from central line elements and fixed box reactions, are equivalent in the toothed models, representing the same rigidity and strength. Although for the smooth models results are clearly distinct, and both strength and stiffness. Comparing models, an approximation of strength is observed when the smooth plate model measurements are considered in the box reaction.

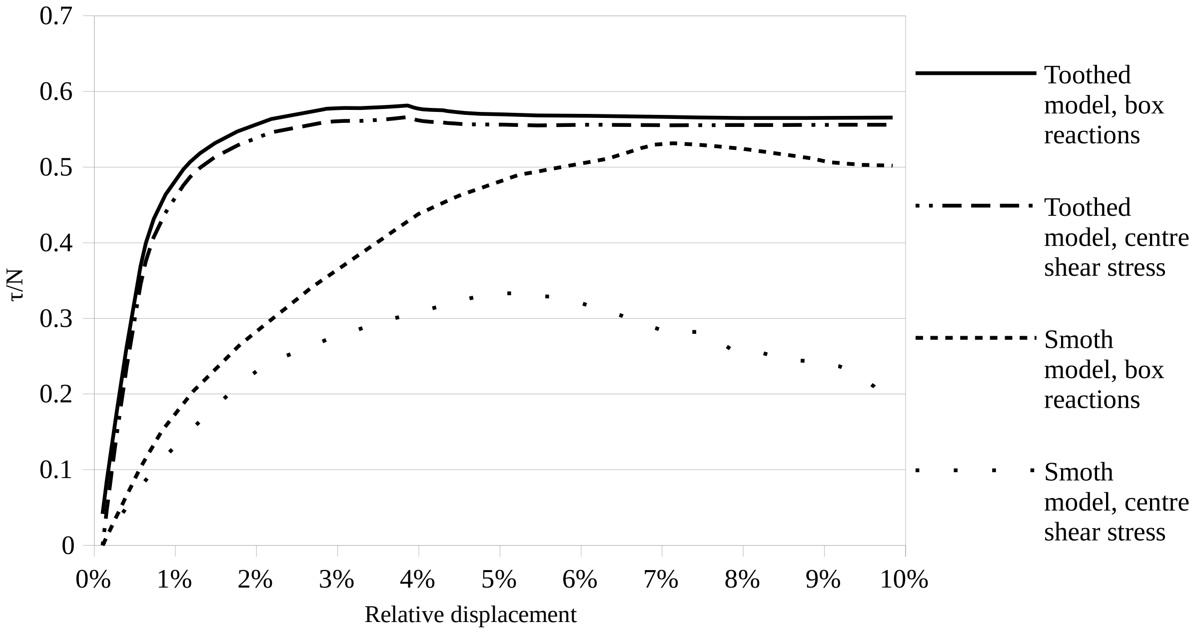

Figure 7. Data collection methods comparison

Continuing the analysis, Fig. 8 and 9 show the horizontal displacements of the models (*U1*) with the toothed plates and smooth plates, respectively, at the maximum strength developed. The colour scale represents ranges of displacement; thus, it is noted that the displacements along with the toothed plates (Fig. 8) have similar levels, generating a uniform distribution of stress. On the other hand, the smooth plates model (Fig. 9) was not effective in moving the soil.

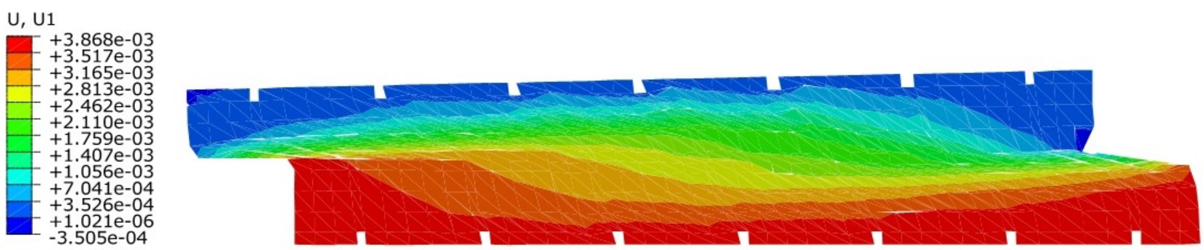

Figure 8. Horizontal displacements in the toothed model

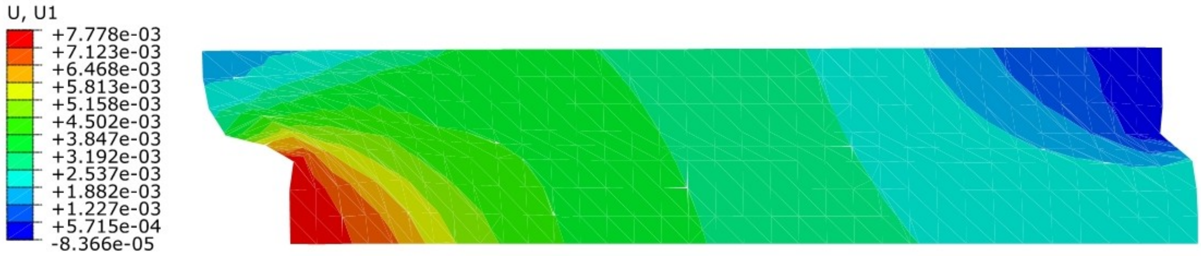

Figure 9. Horizontal displacements in the smooth model

In complement Fig. 10 and 11 show for the same sample, the shear stress development (*S12*). It is noted that the stress distribution is more homogeneous within the sample in the toothed case. Whereas, with the smooth plates, there are areas near the sides with high values of tension in comparative with the centre of the sample, generated by the poor distribution of the displacements.

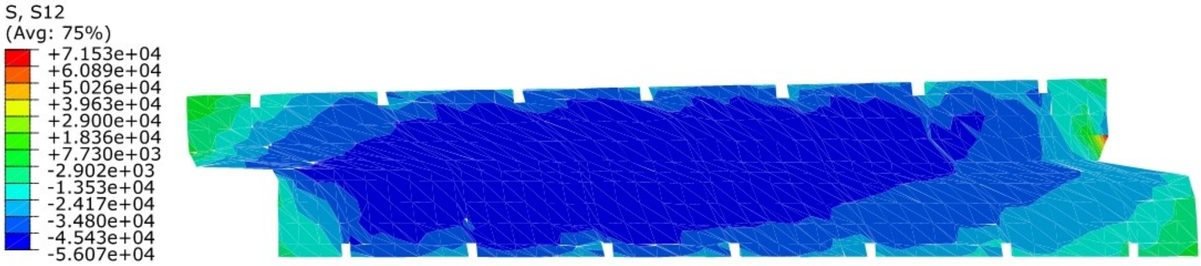

Figure 10. Shear stress in the toothed model

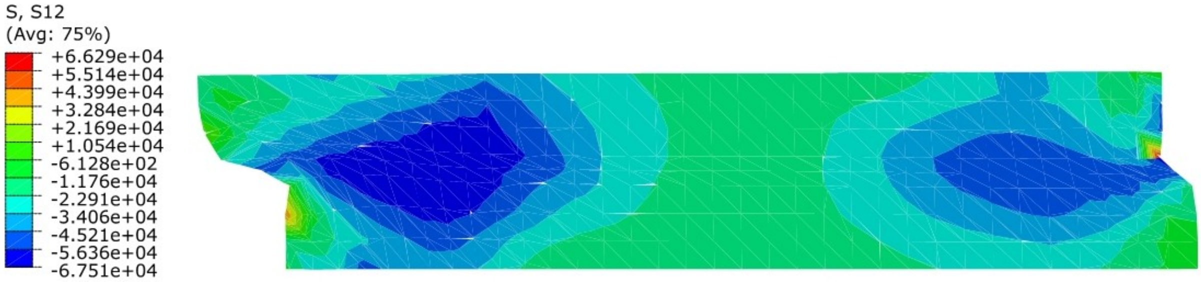

Figure 11. Shear stress in the smooth model

Complementary to this analysis, the stress transfered to the plates and side boxes were investigated to analyse the failure propagation. The idea is observe if one element is more mobilized than the other and the implications of it. The results of the load transmission are presented in Fig. 12 and 13. It is observed that in the toothed model (Fig. 12) there is a constant ratio between the tensions mobilised by the box side and the tensions mobilised by the plate, indicating a good distribution of tensions. Also, the plates are responsible for mobilising most of the stresses in the specimen during the shear phase. On the other hand, when the stresses mobilised by the same elements are analysed in the smooth plates model (Fig. 13), a similar initial tendency of the constant ratio is noted, but the tension mobilised by the smooth plate reaches a limit, connected to the surface friction angle, while the reaction on the side of the box keeps increasing, which indicates that the failure zone has shifted to the interface.

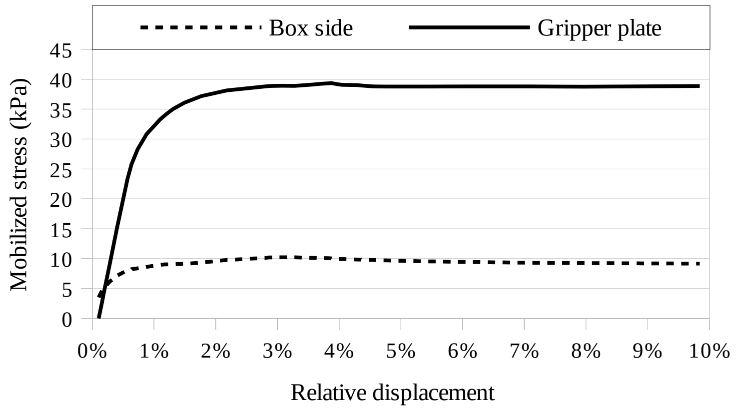

Figure 12. Transference of stress through the elements of toothed model

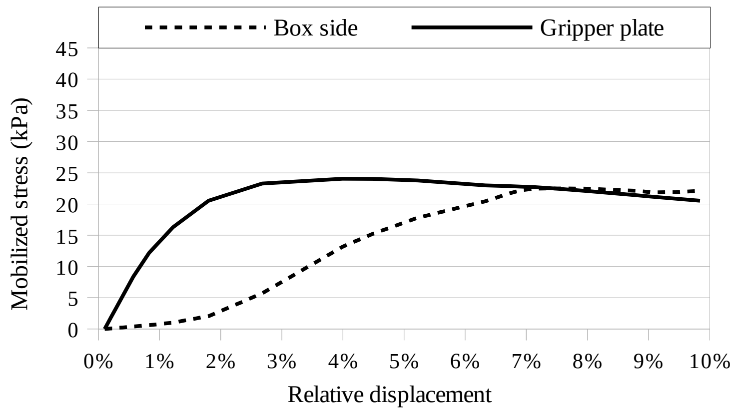

Figure 13. Transference of stress through the elements of smooth model

As already described, direct shearing test is intended to obtain the shear strength parameters of the soil. Those parameters are usually obtained from the reactions readings on the fixed box and the applied normal stresses. Based on this procedure Fig. 14 and Table 2 shows the interpretation of the failure envelope based on the numerical readings of the fixed box reactions in both models, smooth and toothed.

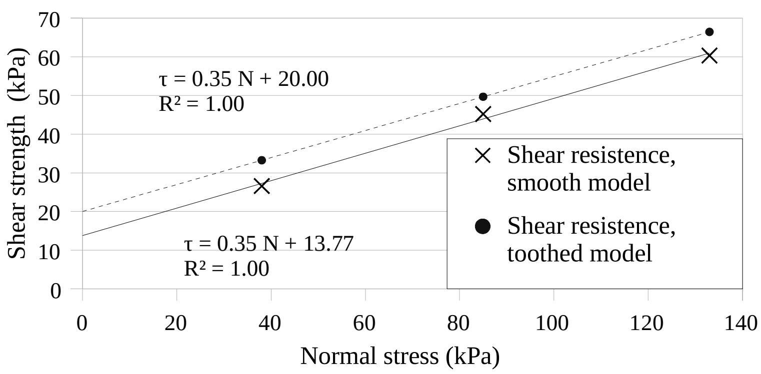

Figure 14. Simulated test

Observing Fig. 14 and Table 2, it is noted a difference between the failure envelop obtained by the numerical simulations with smooth plates and the expected parameters. This difference is more pronounced in the cohesive parameter. In contrast, the envelope parameters values obtained through the toothed models are similar to the expected values, thus showing that the adhesion of the soil and plate is important to characterization of failure.

Table 2. Simulated test: results

Paramater	Aspected values	Toothed model	Smooth model	Difference
τ_f (N = 38 kPa)	33.8	33,4	26,6	-20%
τ_f (N = 85 kPa)	50.9	49,4	45,2	-9%
τ_f (N = 133 kPa)	68.4	66,2	60,3	-9%
c (kPa)	20	20,2	13,7	-32%
ϕ (kPa)	20	19,5	19,1	-2%

5 Conclusions

The present work aims to study the stresses and strains in the sample during the execution of the direct shear test using models based on finite elements (FEM). Two geometric representation were evaluated to verify the influence of the adhesion of the gripper plates to the sample during the direct shear test: one of these models with toothed plates and another with a smooth plate.

In a preliminary analysis of the developed finite element model of the toothed plates, it was verified that the two-dimensional geometry, coupled with the elastoplastic behaviour, were efficient in representing the typical curves of the direct shear test experimentally obtained from Godoi [11].

The smooth plate models may represent the situation of poor adhesion or non-crimping of the gripper plates. During the shear phase of these modelling, the failure surface may form a wedge toward the contact surface between the gripper plate and the sample. Observing the result of this model it was found that when the adhesion between the gripper plate and the soil sample is poor, the resulting failure envelope obtained from the reactions readings on the fixed box and the applied normal stresses has its parameters changed. The interpretation in these cases is impaired.

Finally, the results of this work show that for the execution of the direct shear test, the use of the toothed plate is still necessary. Also, after each stage of the test, it is necessary to check whether the failure surface has developed in the centre of the sample. If this requirement is not met, the test results may be compromised.

References

[1] K. H. Head and R. J. Epps. *Manual of soil laboratory testing, Volume II: permeability, Shear strength and compressibility tests.* Whittles Publishing, 2011.

[2] C. S. Pinto. *Curso básico de mecânica dos solos em 16 aulas.* Oficina de textos, 2006.

[3] A. Drescher. Discussion of “Numerical Analysis of Drained Direct and Simple Shear Tests” by Andrew Drescher. *Journal of Geotechnical Engineering*, vol. 121, n. 2, pp. 223-225*,* 1995.

[4] D. M. Potts, G. T. Dounias and P. R. Vaughan. Finite element analysis of the direct shear box test. *Géotechnique*, vol. 37, n. 1 pp. 11-23, 1987.

[5] R. S. Silva. Ensaio de Cisalhamento Direto: Quando a Superfície de Ruptura não Ocorre em um Plano Horizontal. Bachelor's thesis, Universidade Federal de Santa Catarina, 2001.

[6] G. T. Dounias and D. M. Potts, Numerical Analysis of Drained Direct and Simple Shear Tests. *Geotechnical and Geoenvironmental Engineering*, vol. 119, n. 12, pp. 4-6, 1993.

[7] R. Z. Moayed, S. Tamassoki and E. Izadi. Numerical Modeling of Direct Shear Tests on Sandy. *International Journal of Civil, Structural, Construction and Architectural Engineering*, v. 6, n. 1, pp. 943-947, 2012.

[8] A. Salazar, E. Sáez and G. Prado. Modeling the direct shear test of a coarse sand using the 3D Discrete Element Method with a rolling friction model. *Computers and Geotechnics*, vol. 67, pp. 83-89, 2015.

[9] A. Bagherzadeh-Khalkhali and A. A. Mirghasemi. Numerical and experimental direct shear tests for coarse-grained soils. *Particuology*, vol. 7, n. 1, pp 83–91, 2009.
[10] M. M. Dadalto and N. Dakmonech. Ângulo de atrito equivalente do solo e elementos de fundação em concreto, aço e madeira. In: Congresso Técnico Científico da Engenharia e da Agronomia - CONTECC 2015, vol. 1, p. 4.
[11] C. S. Godoi. Caracterização geomecânica de um solo residual de gnaisse – Santo Amaro da Imperatriz, Santa Catarina. Master's thesis, Universidade Federal de Santa Catarina, 2014.
[12] A. H. Teixeira and N. S. Godoy, Análise, projeto e execução de fundações reais. *Fundações: Teoria e prática*, 2ª ed, 1998.