Cost/benefit analysis of constitutive laws and DEM approach for geotechnical simulations under various loading paths

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Cost/benefit analysis of constitutive laws and DEM approach for geotechnical simulations under various loading paths

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1 INTRODUCTION

This work is dedicated to a profound comparison of different soil constitutive relations as well as the DEM method in order to assess the capability of each model to simulate the complex behavior of different types of soil and to quantify the extra cost of more complex approaches in terms of calibration and computation efforts. For generality purposes, two different soils are studied as well as different (drained or undrained) hydro-mechanical conditions. The first type of soil considered is a Tropical soil (Mouali et al. 2019) that is formed by an in-situ weathering of igneous and metamorphic rocks and located in Guadeloupe (French West Indies). This soil could be a representative for the complex behavior of soft clays. The second type of soil considered is a Japanese fine sand called Toyoura sand (Fukushima et al. 1984), whose mechanical response extremely depends upon the initial void ratio and is characterized by a highly nonlinear mechanical response under monotonic and cyclic loading. The mechanical behavior of Toyoura sand and Tropical soil are systematically simulated by using different constitutive laws and a DEM approach.

A vast campaign of numerical simulations of drained and undrained triaxial tests is thus carried out aiming to numerically simulate the behavior of these particular types of soil using one zone element in (axisymmetric) *FLAC* (2011) and *FLAC3D*, whereas a representative volume of the biaxial/2D DEM test is introduced in the *PFC2D* in order to assess the DEM approach. One of the main objectives of this study is to answer the question that is released before any engineering project concerning the cost/benefit of the choice of the numerical model. To answer this question, a study of the accuracy gained from the diverse models versus both computational time and effort of the calibration process is carried out.

The numerical simulation of the tropical soil is performed using different soil constitutive relations initially starting from the classical Elastic-Perfectly plastic “Mohr-Coulomb” model with one failure envelope and a simple flow rule, then increasing the complexity and passing by the frictional hardening model by (Vermeer et al. 1984); modified Cam Clay by (Roscoe et al. 1968), that are both considered as hardening/softening elastoplastic models; as well as the Cap-Yield model that permits the volumetric hardening (elliptic volumetric cap) to evolve in an uncoupled fashion from the shear frictional hardening. Finally, ending with a most complex approach that uses DEM direct simulations in *PFC2D* by considering a representative volume that could represent one zone in *FLAC* which could be involved in a multiscale simulation (Miehe et al. 2010) and (Nguyen et al. 2014). A multi-scale modeling framework could be introduced by coupling finite-difference method (FDM) *FLAC* and discrete-element method (DEM) *PFC2D*. However, the computational cost of this method remains the main obstacle for the practical problems.

As for Toyoura sand, we take into account refined relations such as P2PSand model which is a developed model of the DM04 model (Dafalias et al. 2004) or the CJS model (Duriez et al. 2015). These models are established in the framework of bounding surface plasticity or classical elasto-plasticity, in which those relations depend on the initial relative density of the soil (in terms of both the void ratio and the mean pressure) and consider the fabric evolution of grains contact direction that reflect into an anisotropy of the granular material. These micro-scale dependencies strengthen the abilities of those approaches for describing an evolving behavior throughout cyclic loading.

2 RESULTS AND DISCUSSION

The results of the numerical simulation for the tropical soil in drained and undrained conditions show a satisfying agreement with the experimental results. For example, Figures 1c, d show simulation results together with experimental data (Mouali et al. 2019) of triaxial drained compression test on a Tropical soil specimen with different mean effective stress values. The results of the Hardening-Softening model show an excellent agreement with the tested data for both deviatoric stress and volumetric strain versus vertical strain, since the hardening behavior in this model is totally controlled by the user. Whereas for the Cap-Yield model, a good agreement is achieved for the deviatoric stress versus axial strain response but with the same form of the volumetric strain for different values of mean effective stress that could imply the non-dependency of the flow rule on the mean stress of the sample. This behavior is also noticed in the simulation of the Modified Cam-Clay model whose flow rule does not depend on the mean stress and only depends on the constant intrinsic parameters of the model. Finally, a rough bi-linear behavior is observed by using Mohr-Coulomb model (Figs. 2a, b) with a capability to follow the continuous contraction behavior of the tropical soil by introducing a negative dilatancy value.

It seems that the experimental drained triaxial test didn't reach a well-defined critical state, since the critical state is expected well beyond 14% and for this reason, an additional experimental data (Futai et al. 2004) of the Tropical soil is used. The numerical fitting for this data in drained and undrained triaxial test is performed using Cap-Yield model, shows a very good agreement with the experimented results.

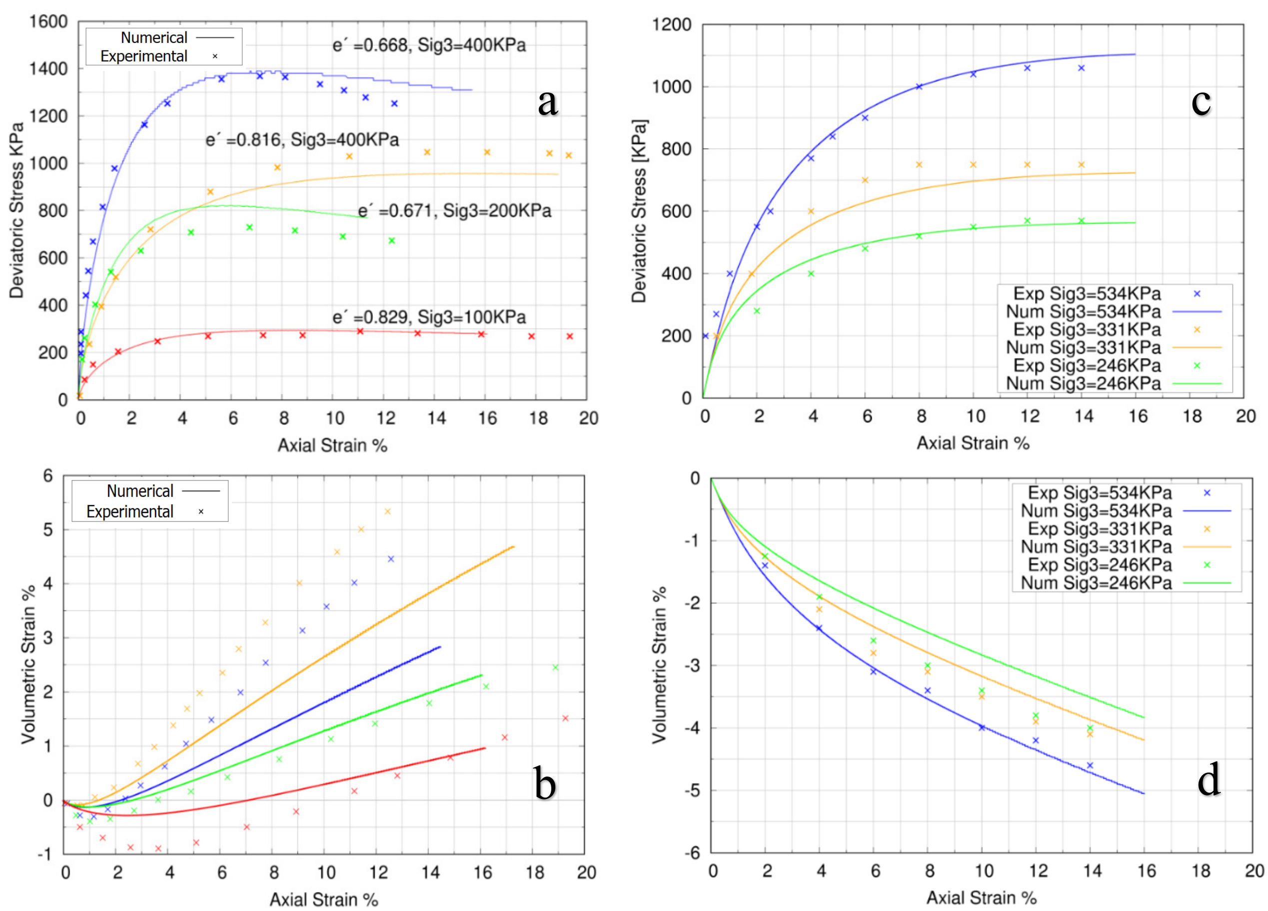

Figure 1. a) Deviatoric Stress vs Axial Strain for Toyoura Sand P2PSand model. b) Volumetric Strain vs Axial Strain for Toyoura Sand P2PSand model. c) Deviatoric Stress vs Axial Strain for Tropical (Soil Hardening Softening model) d) Volumetric Strain vs Axial Strain for Tropical Soil (Soil Hardening Softening model).

As for the DEM simulation of the Tropical soil using a parallel bond contact model (Figs 2-a, b) for a biaxial test, a good agreement is attained with the experimental result of the drained triaxial test. However, a small dilatancy behavior was observed at a large strain value which is a direct response for the broken bond between the particles. Regarding the validation of the parallel bond contact model with different values of mean stress, the validation shows that the volumetric strain depends on the mean stress value. This behavior was not observed in the simulation of Tropical soil with Modified Cam-Clay and Cap-Yield models. Regarding this comparison, it is worth mention that only a qualitative comparison should be established between the result of the *PFC2D* (Biaxial Test) and *FLAC3D* (Triaxial test) because there is a difference in the nature of both tests.

Concerning Toyoura sand, the numerical simulation of drained and undrained triaxial tests by using P2PSand model shows a very good agreement with their corresponding experimental triaxial tests. For example, Figures 1-a, b show simulation results together with experimental data (Fuhushima et al. 1984) for triaxial drained compression test on Toyoura sand soil specimen with different values of initial void ratio and mean effective stress, meanwhile there is still a slight difficulty to follow the full dilatant behavior for different values of mean pressure and initial void ratio.

Finally, regarding the calculation time, it is actually remarked that the computational time of one zone in a drained triaxial test and in *FLAC3D* is higher than the computational time of one zone element in *FLAC* for the same test. On the other hand, a comparison performed between the computational time of "Mohr-Coulomb", "Modified Cam Clay" in *FLAC* and Parallel bond model with one thousand spheres in *PFC2D* model were found to be 7.27sec, 7.48sec and 2.20 min respectively.

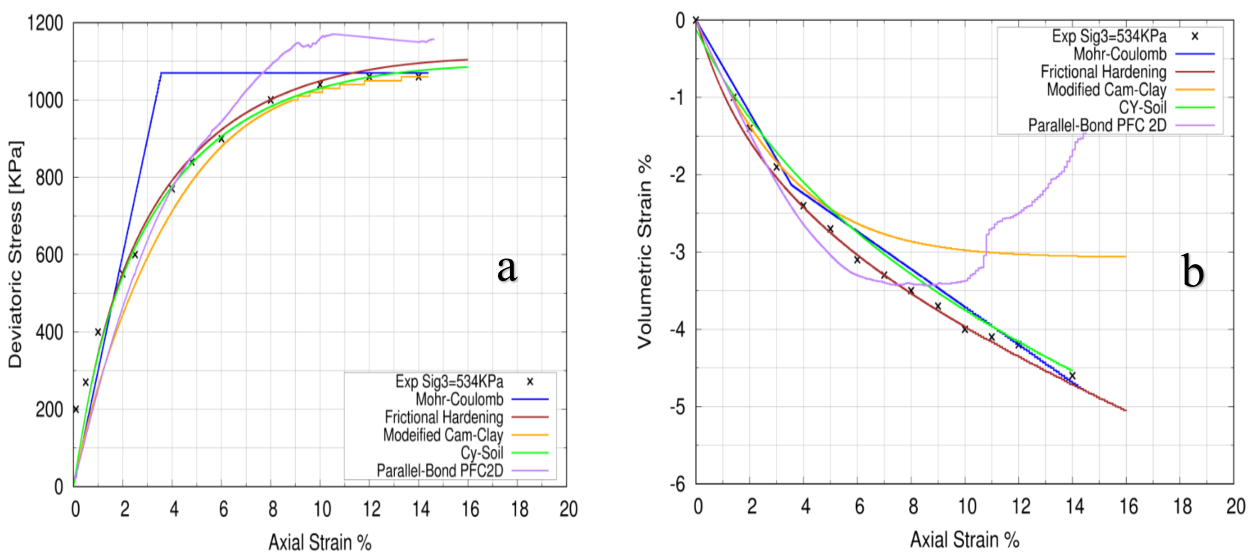

Figure 2. a) Deviatoric Stress vs Axial Strain of Tropical Soil with different models. b) Volumetric Strain vs Axial Strain of Tropical soil with different models.

3 CONCLUSIONS

This study presents a deeper insight into the different soil models and DEM approach in terms of their accuracy balanced with calculation time and calibration effort and starting from less complex to most complex models.

As for the Tropical soil, different models logically produced results with an increasing accuracy along the increase of the constitutive complexity. Regarding the simulation of the biaxial DEM model and by using the parallel bond contact model, the result is qualitatively coherent with the drained triaxial experimental result of Tropical soil.

The P2PSand model shows a high capability to simulate the high nonlinear behavior of Toyoura sand for the drained and undrained triaxial test, but still needing a slight adjustment for the volumetric change response.

Finally, the calculation time is higher in *FLAC3D* than in *FLAC* for the same test, for one zone and for the same commands used. However, in *FLAC* and for different soil models used in this study, there is no significant change in the computational time. Meanwhile, the calibration efforts increase with the increase of the complexity of the models but with higher accuracy.

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