

Introduction of automatic calibration software for advanced soil constitutive models

Introduction d'un logiciel d'étalonnage automatique pour les modèles constitutifs avancés du sol

T. Kadlicek¹, T. Janda², D. Masin¹, M. Sejnoha², S. Benes², J. Najser¹, I. Sula¹

¹Charles University, Prague, Czech Republic

²Czech Technical University, Prague, Czech Republic

ABSTRACT: This paper presents the online calibration application called ExCalibre developed in cooperation of Charles University in Prague, Czech Technical University and Arcadis Ltd. The calibration is currently available for the elastoplastic Modified Cam-Clay model, hypoplastic sand and hypoplastic clay model. A successful calibration requires data of basic laboratory experiments such as oedometric or isotropic compression test and drained or undrained triaxial shear test. The experiment data has to be prepared in the predefined excel format which is uploaded before the calibration. The application benefits from a clear physical meaning of the aforementioned advanced constitutive models' parameters and employs Newton's optimization method for the further optimization. Thorough testing of developed calibration procedures proved ExCalibre to be a reliable and powerful calibration tool for both academic and practical purposes.

RÉSUMÉ: Cet article présente l'application d'étalonnage en ligne ExCalibre développée en coopération avec l'Université Charles de Prague, l'Université technique tchèque et Arcadis Ltd. La calibration est actuellement disponible pour le modèle Cam-Clay modifié élastoplastique, le modèle de sable hypoplastique et l'argile hypoplastique. Un étalonnage réussi nécessite des données d'expériences de laboratoire de base telles que le test de compression oedométrique ou isotrope et le test de cisaillement triaxial drainé ou non drainé. Les données de l'expérience doivent être préparées dans le format Excel prédéfini qui est téléchargé avant l'étalonnage. L'application bénéficie d'une signification physique claire des modèles constitutifs avancés susmentionnés et utilise la méthode d'optimisation de Newton pour une optimisation ultérieure. Des tests approfondis des procédures de calibration développées ont montré qu'ExCalibre était un outil de calibration puissant et fiable, à la fois académique et pratique

Keywords: Calibration; hypoplasticity; elastoplasticity

1 INTRODUCTION

Constitutive models and finite element softwares are nowadays inseparable tools from the geotechnical calculations. Accuracy of these calculations is affected by numerous issues linked not only to the geometry of the finite element

model but the most notably to the selected constitutive model. In spite of the fact that there are available countless advanced critical state based constitutive models, the basic elastoplastic models in the various modifications are often employed. Consequently, application of the recent

hypoplastic models remains limited to the academic studies since an ordinary engineer does not possess a tool nor knowledge necessary for a reliable calibration of the advanced constitutive models. Therefore, a tool that would provide a prompt and reliable calibration of the models' parameters would be appreciated as it saves not only time required for the calibration but also enables to create a save and possibly more economical design.

The calibration procedure is regarded as an inverse analysis since parameters \mathbf{m} of a constitutive model are not known in advance, however the reaction \mathbf{R} of the system \mathbf{S} to the action \mathbf{A} is (Zentar, 2001, Yin, 2018), see Eq. (1).

$$\mathbf{A} \Rightarrow \mathbf{S}(\mathbf{M}, \mathbf{m}) \Rightarrow \mathbf{R} \quad (1)$$

Calibration tools can be divided according to the optimization methods used for the minimization of the error function \mathbf{E} characterizing a difference between a measurement and simulation.

The stochastic methods generate random variables while minimizing the error function \mathbf{E} . These methods often provide nonunique solution while the best result can be selected based on the user's experiences. It is worth pointing out that stochastic methods are time consuming. The deterministic methods on the other hand does not employ a method of the random search and the method always generates the same solution for a given problem. Although the advantage of these methods is a prompt converging towards a solution, the solution is highly influenced by the initial parameter's estimation, furthermore, more problems can be encountered in the case of the parameters' strong coupling effects.

These inconveniences can be overcome provided that a clear physical meaning of the parameters is given and thus the correct solution is in the close proximity. Comparison of both methods can be found in (Levasseur, 2008) and (Papon, 2012).

In the cooperation of Czech Technical University in Prague, Charles University and SG Geotechnika formerly Arcadis Ltd. was developed a calibration software ExCalibre. This software works as an online application which currently enables calibration of the elastoplastic Modified Cam-Clay model (Roscoe, 1968), hypoplastic sand (Wolffersdorff, 1996) and hypoplastic clay model (Masin 2013). To minimize the error function \mathbf{E} , the calibration software ExCalibre employs Newton's optimization methods and takes an advantage of the parameters' physical meaning.

2 CONSTITUTIVE MODELS

ExCalibre enables to calibrate three advanced constitutive models which parameters are described in following sections.

2.1 Elastoplastic Cam-Clay model

The Modified Cam-Clay (MCC) model is probably the best known critical state soil model. This model not only successfully incorporated an effect of the soil's density and stress level on the soil's stiffness but also predicts a soil's failure at the unique combination of stress and void ratio e .

Even though Cam-Clay is the elastoplastic model it predicts a nonlinear elastic behaviour upon a loading and unloading inside the yield surface and plastic nonlinear behaviour once the state occurs at the yield surface and further loading is applied. The typical feature of the Cam-Clay model is an expansion of the yield surface during the isotropic hardening.

Cam-Clay model is defined by these five parameters λ , κ , e_0 , M_{cs} and ν . The parameter λ is defined as the slope of the normal consolidation line (NCL) in a semilogarithmic space $\ln p \times e$. Similarly, a slope of the swelling line is defined by the parameter κ . The isotropic NCL is positioned in $\ln p \times e$ by the parameter e_0 . The slope of the critical state line (CSL) in $p \times q$ space is defined by the parameter M_{cs} which is a

function of the critical state friction angle φ_c . The last parameter is Poisson's ratio ν .

A shape of the yield surface is an ellipse in the meridian plane and circular in the deviatoric plane, see Figure 1. Consequently, the MCC model overestimates the peak friction angle φ_p of overconsolidated soils. In addition, M_{cs} has to be set to a specific value in order to fit either triaxial compression or triaxial extension data.

2.2 Hypoplastic sand model

The theory of hypoplasticity, as it is considered today, was proposed in (Wu, 1990) as a alternative to the elastoplasticity. Unlike the elastoplasticity, however, the hypoplasticity does not possess a typical switch function but the stress strain evolution is governed by a single equation, furthermore, hypoplasticity does not divide the total strain into the elastic and plastic components.

The hypoplastic model for sand referred in this article was proposed in (Wolffersdorff, 1996), where the sound form of the hypoplastic equation with a precisely predefined limit surface was established. The proposed limit surface depicted in Figure 2 is of Matsuoka-Nakai shape and deviatoric space and of Drucker-Prager in the meridian plane.

The hypoplastic sand model is defined by eight parameters. The parameters h_s and n controls a slope and curvature of the isotropic NCL while its position in $p \times e$ is defined by the parameter e_{i0} . In addition, the critical state line and the line of the highest density are similarly defined in $p \times e$ and their evolution is also driven by the parameters h_s and n . Positions of these are defined by the parameters e_{c0} for the critical state line and e_{d0} for line of the highest density, see Figure 3.

The parameter β controls a stiffness of the model in relation to CSL. The parameter α controls the peak friction angle φ_p in relation to the relative density r_e . The last defined parameter is the critical state friction angle φ_c .

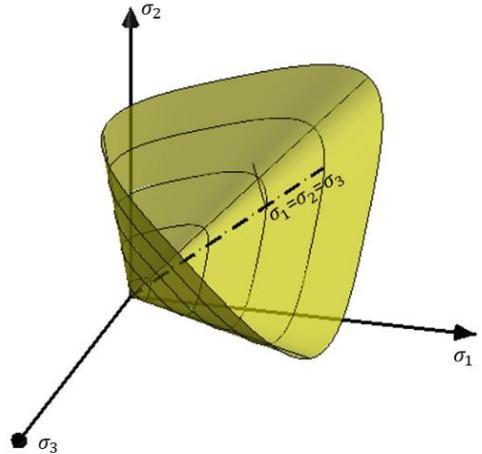


Figure 2. Limit surface of hypoplastic sand model

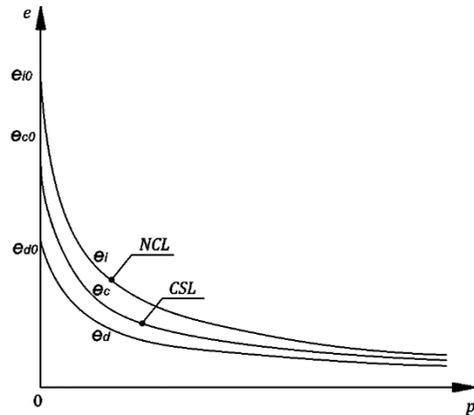


Figure 3. Parameters of hypoplastic sand model

2.3 Hypoplastic clay model

It was discussed in (Herle, 2004) that the Wolffersdorff's hypoplastic model does not properly simulate the behaviour of clays, e.g. it underestimates a stiffness for a low critical state friction angle and predicts a non-zero void ratio, in addition the swelling line cannot be directly calculated as it is influenced by both parameters α and β . Masin thus proposed new hypoplastic model for clays adopting a layout proposed for MCC and was later improved in (Masin, 2013). This model is currently adopted in ExCalibre.

Hypoplastic clay model is defined by five parameters closely resembling those of MCC. The parameter λ^* defines the slope of the NCL in $\ln p \times \ln(e + 1)$ space while the vertical position of the isotropic NCL is specified by the parameter N . The swelling line is defined by the parameter κ^* . Similarly to the MCC, hypoplastic clay model defines the critical state friction angle φ_c . The remaining parameter is Poisson's ratio ν controlling a ratio of bulk K_i and shear G_i modulus and the isotropic state.

The shape of the state boundary surface is drop-like shape in the meridian plane and Matsuoka-Nakai in the deviatoric plane, see Figure 4.

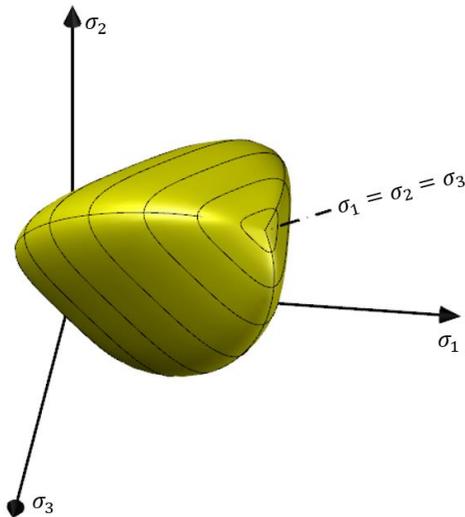


Figure 4. Boundary surface of hypoplastic clay model

3 EXCALIBRE

The calibration procedures recommended for hypoplastic sand and hypoplastic clay models can be found in (Herle, 1999) and (Masin, 2013) respectively and will not be discussed in the following sections.

The calibration software ExCalibre is developed as an online application available on the website:

soilmodels.com/excalibre/

During the development of the application, the emphasis was put on the physical meaning of the parameters and calibration speed. The calibration is available for three constitutive models, namely Elastoplastic Cam-Clay and hypoplastic models for sand and clay. The future plans aim to add a calibration for the small strain stiffness of the hypoplastic models.

To properly establish the calibration and iteration procedures, the sensitivity analysis was conducted in order to properly specify the impact of each individual parameter. The sensitivity was tested on the compression as well as triaxial shear tests with respect to a deformation and stress discrepancies between a simulation and experiment. Developed calibration and iteration procedures were further coordinated and verified between the developers of the software.

Figure 5 depicts a structure of the ExCalibre software which is consisting of two distinct sections. The first section enables a simulation of laboratory experiments for three aforementioned models while soil sample state and loading condition has to be defined. The second section is the calibration itself. Both simulation and calibration call a method Driver which includes single element libraries for all three constitutive models.

The calibration requires uploading of the laboratory experiment records ordered in the pre-defined form. The template of the excel data file is available to be downloaded at the website. It is also possible to download a filled excel data files for 33 different locations from the website's library which also displays calibrated parameters and USCS classification with other soil's specifications.

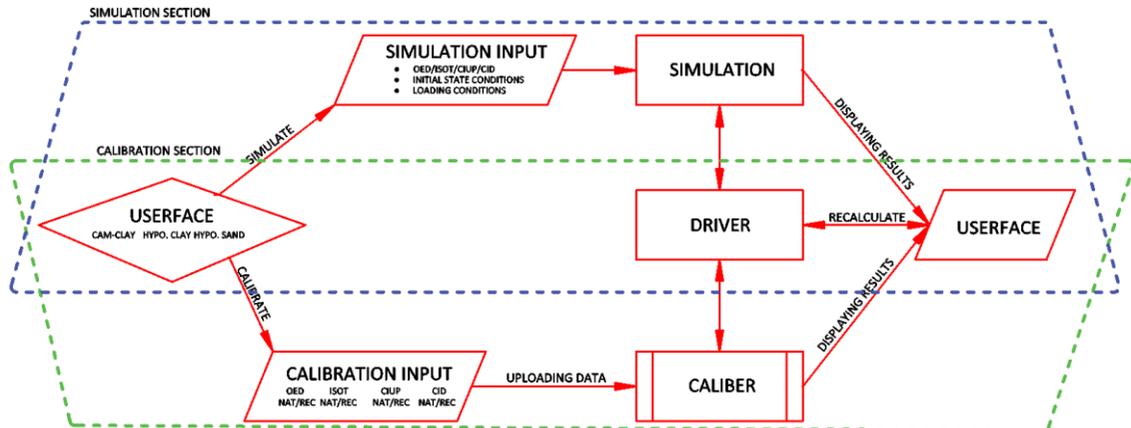


Figure 5 Diagram of the ExCalibre application

To run the calibration successfully the data file has to contain at least one oedometric or isotropic compression experiment and at least one triaxial drained or undrained experiment as the models' parameters are preferably calibrated on different experiments. The ExCalibre software also takes an advantage of the differences between a natural undisturbed specimen and reconstituted specimen. It was observed that the asymptote controlling parameters such as λ^* and N are better established on the reconstituted specimens while the stiffness controlling parameters such as ν is more representatively established on the natural specimen in order to capture effect of specimen's structure. The user can upload a data file with as many experiments as needed in order to obtain a better picture of the soil behaviour and ExCalibre will provide the best possible combination of parameters to represent soil's behaviour. However, it is worth noting that adding experiment records increase the time required for the calibration.

Hereinafter are illustrated the results of the calibration for all three constitutive models.

3.1 Elastoplastic Cam-Clay model

The MCC model was calibrated for the specimen designated as Bilina 5. The data file containing the experiments' records of this location is also available on the Excalibre's website. The file

contains the records of one natural and one reconstituted oedometric experiment and three natural and three reconstituted undrained triaxial shear experiments. According to USCS, the soil specimen is classified as CH.

The calibration results are compared with experiment records for the reconstituted oedometric tests in Figure 6 and natural oedometric test in Figure 7. The undrained triaxial tests of natural specimens are displayed in Figure 8.

A typical elastoplastic behaviour can be observed in all three figures as a sudden change in the soil stiffness and failure appears. It is worth noting that the isotropic compression normal compression line parameters λ and e_0 is calibrated on the reconstituted oedometric specimen and the parameter κ on the natural specimen.

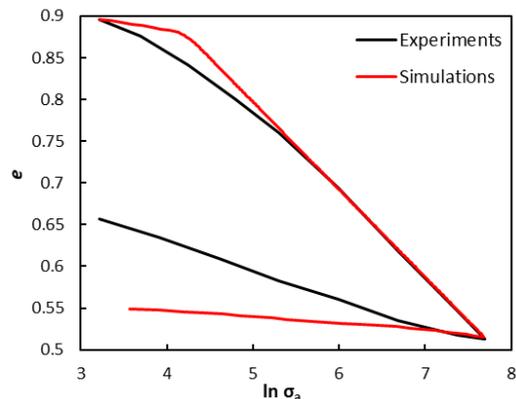


Figure. 6 Oedometric test – reconstituted specimen

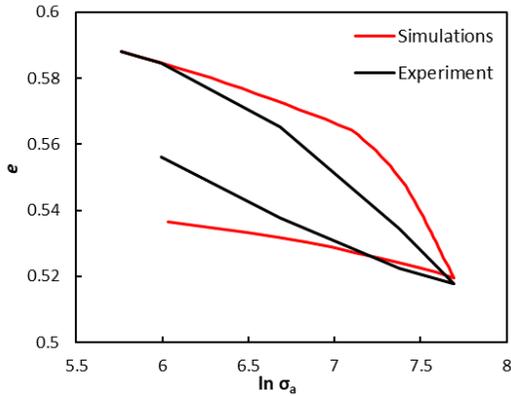


Figure. 6 Oedometric test – natural specimen

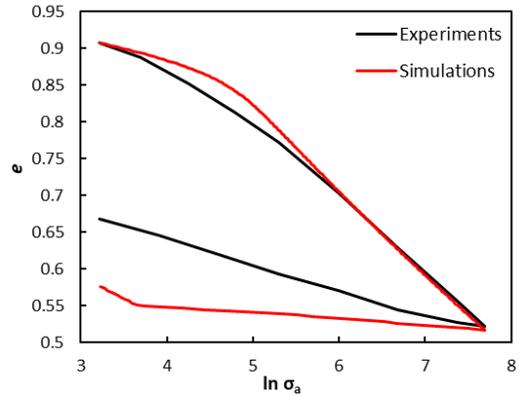


Figure. 8 Oedometric test – reconstituted specimen

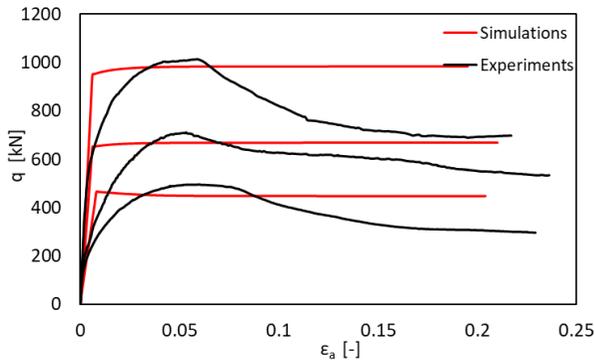


Figure. 7 Undrained triaxial test – natural specimen

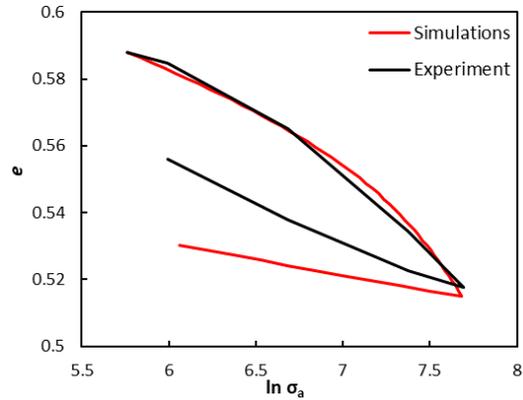


Figure. 9 Oedometric test – natural specimen

The parameters calibrated for the MCC model are displayed in the Table1.

Table 1. MCC model's parameters

Parameter	Value
λ	0.104
κ	0.026
e_0	1.31
M_{cs}	0.888
ν	0.2

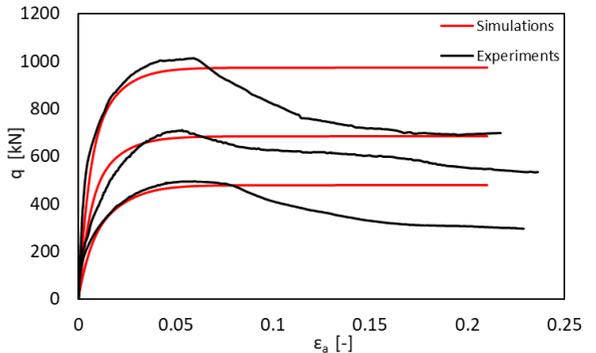


Figure. 10 Undrained triaxial test – natural specimen

3.2 Hypoplastic clay model

The calibration of the hypoplastic clay model is conducted on the same data file designated Bilina 5 as in the case of MCC. Results of the calibration are again depicted in Figure 8 and 9 for oedometric test and in Figure 10 for undrained triaxial test of the natural specimens.

When comparing the calibration results of both MCC and hypoplastic clay model, the prediction capabilities and limitations of MCC model are evident. The hypoplastic clay model well predicts

a stiffness degradation before the critical state occurs.

Results of the calibration executed for the hypoplastic clay model are displayed in Table 2.

Table 2. Hypoplastic clay model's parameters

Parameter	Value
λ^*	0.069
κ^*	0.007
N	0.947
φ_{cs}	22.7
ν	0.31

3.3 Hypoplastic sand model

The hypoplastic sand model was calibrated on the specimen designated as Dobrany, which is also available in the website library. The data file is consisting of one oedometric test and three drained triaxial tests. According to the USCS, the specimen is classified as SW.

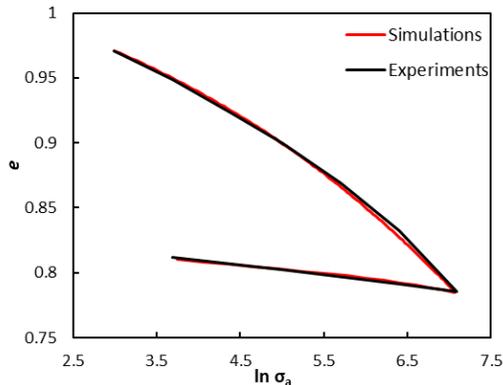


Figure. 11 Undrained triaxial tests

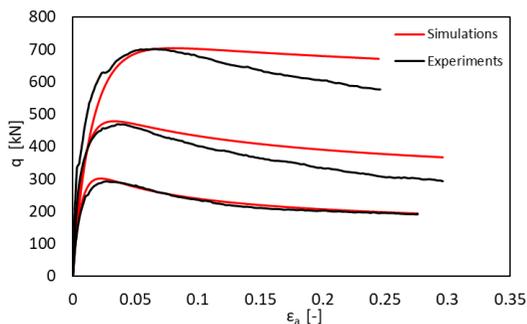


Figure. 12 Undrained triaxial tests

The results of the calibration illustrated in Figures 11 and 12 depicts a good match with the experimental data. The values of the calibrated parameters are summarized in Table 3.

Table 3. Hypoplastic sand model's parameters

Parameter	Value
hs	44,793
n	0.185
e_{i0}	1.523
e_{c0}	1.269
e_{d0}	0.635
α	0.1
β	4
φ_{cs}	36.5

3.4 Results

It is worth noting that the calibration results are severely influenced by the conditions of data used for the calibration. Incomplete experiment's data or possible errors thus consequently may cause unreliable calibration results.

Once the calibration is finished, the results are displayed in separate tabs including the charts for each individual experiment with plotted simulation. In addition, ExCalibre enables to change model's parameters as well as soil initial void ratio and recalculate the simulation. The new simulations are plotted into the existing charts for a better comparison.

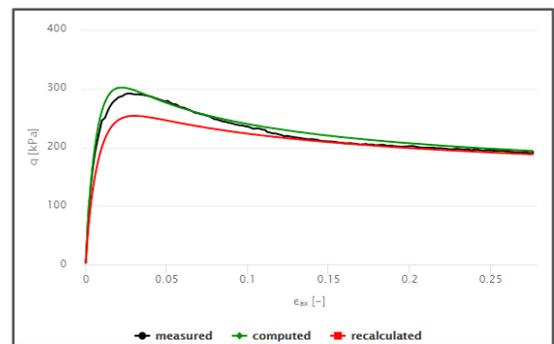


Figure. 13 ExCalibre results with recalculation

This feature is well illustrated in Figure 13 where both initial calibration results (green) and recalculated results (red) are plotted against undrained triaxial records (black). The figure is taken from the ExCalibre application results.

If necessary, the recalculation provides a convenient tool for the parameters' optimization according to the user's need or preferences.

In the case that the simulated data is required to be obtained, the table of state variable for each iteration step can be opened and extracted.

4 CONCLUSIONS

The calibration software ExCalibre represents an useful tool for the evaluation of the advanced constitutive models' parameters where the necessary knowledge or tools for a reliable calibration are lacking. ExCalibre is thus appreciated not only on the level of an ordinary engineer but also on the level of a scientist as the calibration is prompt and requires a minimum user's interventions.

5 ACKNOWLEDGEMENTS

The financial support provided by the project TA04031603 is gratefully acknowledged.

6 REFERENCES

- Zentar, R., Hicher, P. Y., Moulin G., "Identification of soil parameters by inverse analysis," *Computers and Geotechnics*, vol. 28, no. 2, pp. 129–144, 2001.
- Yin, Z. Y., Jin, Y.-F., Shen, J. S., Hicher, P.-Y., "Optimization techniques for identifying soil parameters in geotechnical engineering: Comparative study and enhancement," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 42, no. 1, pp. 70–94, 2018.
- Levasseur, S., Malécot, Y., Boulon, M., Flavigny, E., Soil parameter identification using a genetic algorithm, *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 32, no. 2, pp. 189–213, 2008.
- Papon, A., Riou, Y., Dano, C., Hicher, P.-Y., Single- and multiobjective genetic algorithm optimization for identifying soil parameters, *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 36, no. 5, pp. 597–618, 2012.
- Roscoe, K., Burland, J., On the generalised stress–strain behaviour of "wet" clay, 1968, vol. 14, no. 3.
- Masin, D., Clay hypoplasticity with explicitly defined asymptotic states, *Acta Geotechnica*, pp. 481–496, 2013.
- Wolffersdorff, P. A., A hypoplastic relation for granular materials with a predefined limit state surfaces, *Mechanics of cohesive-frictional materials*, vol. 1, pp. 251–271, 1996.
- Wu, W., & Kolymbas, D. (1990). Numerical testing of the stability criterion for hypoplastic constitutive equations. *Mechanics of Materials*, 9(3), 245-253.
- Herle, I., Kolymbas, D., Hypoplasticity for soils with low friction angles, *Computers and Geotechnics*, vol. 31, no. 5, pp. 365–373, 2004
- Masin, D., Clay hypoplasticity with explicitly defined asymptotic states, *Acta Geotechnica*, pp. 481–496, 2013.
- Herle, I., Gudehus, G., Determination of parameters of a hypoplastic constitutive model from properties of grain assemblies, *Mechanics of Cohesive-frictional Materials: An International Journal on Experiments, Modelling and Computation of Materials and Structures*, vol. 4, no. 5, pp. 461–486, 1999.