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# Simulation of CPT penetration in sensitive clay

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ABSTRACT: This paper presents the results from numerical simulations of CPTu penetration in a natural clay combining the SCLAY1S constitutive model with a large deformation Finite Element framework including a coupled deformation and porewater pressure formulation. The hierarchical model formulation of SCLAY1S captures many features of a natural sensitive clay, such as the evolving anisotropic strength-stiffness response, as well as the degradation of the initial bonding. A sensitivity analysis is performed varying the overconsolidation ratio (*QCR*), bonding and anisotropy, also the hydraulic conductivity (hence, $c_v$) of the clay. The findings indicate that some soil properties (the $c_v$ and *OCR*) impact both the normalised cone resistance $Q_t$ and the generation of excess porewater pressures. In contrast the sensitivity $S_t$ of soft soils primarily affects $Q_t$. In the current work it seems that the effects of the inherent and stress induced (from CPT penetration) anisotropy is not detected using these normalised plots.

## 1 INTRODUCTION

The cone penetration test is a widely used method to perform geotechnical site investigation, by continuous measuring of the cone resistance, the sleeve friction, and in case of the piezocone (CPTu) the generated excess porewater pressures, during the penetration into a soil. This allows the mapping of a deposit to be performed in a time-effective manner with a high resolution (Lunne et al. 1997). Further soil characterisation can be performed using classification systems based on statistical correlations of normalised CPTu results against borehole data, see e.g. Robertson (2016) and Schneider et al. (2008). Due to the continuous measurement of the soil response, the CPTu is a great tool to detect differences in the response between and within soil layers by relying on a contrast in hydro-mechanical properties, e.g a change in hydraulic conductivity, overconsolidation ratio or sensitivity (brittleness).

Another approach to establish the relation between soil properties and CPTu response is to use numerical modelling where a prescribed change of a model parameter of a given constitutive model leads to a change in CPTu response. This approach is becoming increasingly more attainable with the ongoing developments for numerical analyses. Three modelling aspects that are necessary for accurate simulation of CPTu penetration are (i) the capability of the Finite Element (FE) code to deal with large deformations (ii) the adequate coupling of deformations and the generation/dissipation of excess porewater pressures (iii) a constitutive model that incorporates the complex features of natural soils.

A number of numerical methods able to simulate the kinematics of CPTu penetration in FE have been reported, among others the Arbitrary Lagrangian Eulerian method (Berg et al. 1996, Walker & Yu 2006), Material Point Method (Ceccato et al. 2016), Geotechnical Particle Finite Element Method (Hauser & Schweiger 2021, Monforte et al. 2021), and remeshing procedures (Hu & Randolph 1998, Orazalin & Whittle 2018, Mahmoodzadeh et al. 2014). In some cases the effects of CPT penetration are captured in an Updated Lagrangian framework (Yi et al. 2012, Konkol & Bałachowski 2018, Mahmoodzadeh et al. 2014).

Some of the studies (Ceccato et al. 2016, Monforte et al. 2021, Yi et al. 2012, Konkol & Bałachowski 2018, Mahmoodzadeh et al. 2014, Orazalin & Whittle 2018) also incorporates a coupled stress formulation enabling the study of partial drainage during penetration. Constitutive models able to describe advanced soil features such as brittleness (Monforte et al. 2021) and anisotropy (Hauser & Schweiger 2021, Orazalin & Whittle 2018) has also been incorporated to simulate CPTu penetration.

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This paper builds upon those previous studies by implementing SCLAY1S in a fully coupled Eulerian Finite Element (FE) framework. Subsequently, the relation between the CPTu response and different soil properties is investigated. The model parameters varied, include the hydraulic conductivity ($k$), the sensitivity of the soil ($S_t$), the fabric anisotropy and the overconsolidation ratio ($OCR$).

## 2 NUMERICAL MODEL

Natural features of soft clay, such as breakage of initial bonding and fabric anisotropy, are captured by the SCLAY1S constitutive model (Koskinen et al. 2002) and (Karstunen et al. 2005). The elasto-plastic model originates from the Modified Cam Clay (MCC) constitutive model (Roscoe & Burland 1968), in addition to the volumetric hardening of MCC, SCLAY1S also incorporates rotational hardening and gradual degradation of bonding due to plastic strains in the soil. In short, the evolution of the initial anisotropy and degradation of strength is controlled by volumetric plastic strains and deviatoric plastic strains in the hardening law. The model is hiearchical, i.e. an appropriate choice of model parameters leads to the (de-) activation of the model features that capture (evolution of) anisotropy and destructuration. Hence, in its simplest form the model formulation becomes identical to MCC.

For the current work, the SCLAY1S model was implemented in the Tochnog Professional (Roddeman 2021) finite element framework that is able to handle large deformations by using an Eulerian description with a fixed mesh, where the solution fields for the stress, material velocity and other state variables of the calculation are advected through the domain. Penetration of the CPTu into the soil is performed with the moving boundary method proposed by Dijkstra et al. (2011). Initially, the cone is considered to be outside of the calculation domain, i.e. above the soil surface, and the desired stress state and other state variables required for the model are prescribed to establish the initial state in the model. The numerical penetration is then performed by defining a geometric entity representing the CPTu and prescribing the penetration velocity $v$ to all nodes in this geometry while simultaneously expanding the geometry downwards with the same penetration velocity.

The axisymmetric nature of the problem is exploited using a 2D simplification where the horizontal soil movement and groundwater flow is prevented perpendicular to the axis of symmetry. The geometry and boundary conditions of the numerical model are presented in Figure 1. The initial stress state is prescribed by the vertical effective stress ($\sigma_v{}'$), initial porewater pressure ($u_0$) and the initial earth pressure coefficient ($K_0$). Horizontal movement is prevented at the far right boundary while keeping the porewater pressure constant to $u_0$, hence allowing for groundwater flow across the boundary. At the bottom boundary, vertical groundwater flow and soil movement is prevented. The top boundary of the domain is modelled with a prescribed vertical load that is in equilibrium with the total vertical stress ($\sigma_v$) and is equal to the sum of $\sigma_v{}'$ and the initial porewater pressure $u_0$. The increase in stress due to the weight of the soil in the domain is set to be zero to create a uniform soil domain.

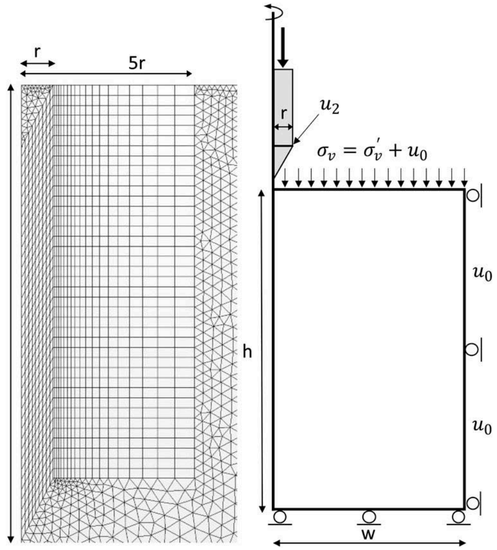


Figure 1. Boundary conditions and mesh in the region close to the penetrating CPTu.

All simulations presented in the study were performed using a 60 cone with a diameter ($d$) of 0.036 m corresponding to a radius ($r$) of 0.018 m. The height of the domain $h$ was set to two times the penetration depth and the width $w$ was set to $40r$, to prevent numerical disturbance related to boundary effects. A structured quadrilateral mesh (see Figure 1) was required in the location of the penetrating cone to ensure geometrical compatibility between the mesh and the penetrating cone that is prescribed with a geometry entity. Quadrilateral elements were used in a region extending 5 cone radii ($r$) from the axis of symmetry. The rest of the domain is filled with unstructured triangular elements. In total, the model contains 1789 quadrilateral elements and 3579 triangular, both with first order shape functions. All simulations in this paper were performed with a penetration rate $v$ of 0.02 m/s down to a final penetration depth of $20d$. The porewater pressure presented in this study was extracted from a position right above the cone shoulder corresponding to the $u_2$ position. The cone resistance $q_c$ was calculated from the total force needed to push the inclined cone tip downwards divided by the area of the cone. The net cone resistance $q_{net}$ was calculated by subtracting the initial vertical stress $\sigma_{v0}$ from the cone resistance $q_c$.

Table 1. Model parameters used to investigate the effect of drainage conditions on the CPTu response.

| Symbol | Parameter | Value |
|---|---|---|
| $\sigma_v{}'$ | Vertical effective stress [kPa] | 109 |
| $u_0$ | Initial porewater pressure [kPa] | 70 |
| $K0$ | Initial earth pressure coefficient [-] | 0.61 |
| $OCR$ | Overconsolidation ratio [-] | 1.02 |
| $e_0$ | Initial void ratio [-] | 1.41 |
| $\lambda$ | Virgin compression index [-] | 0.205 |
| $\kappa$ | Swelling/recompression index [-] | 0.044 |
| $\nu$ | Poisson's ratio | 0.3 |
| $M$ | Slope of CSL line [-] | 0.9 |
| $\chi_0$ | Initial amount of bonding [-] | 0 |
| $a$ | Rate of destructuration [-] | 0 |
| $b$ | Rate of destructuration due to to deviator strain [-] | 0 |
| $\alpha_0$ | Initial anisotropy [-] | 0 |
| $\omega$ | Rate of rotation [-] | 0 |
| $\omega_d$ | Rate of rotation due to deviator strain [-] | 0 |

## 3 VARIATION OF HYDRAULIC CONDUCTIVITY

Initially, the effect of the drainage conditions on the CPTu response was studied using a MCC model formulation, by varying the hydraulic conductivity $k$ in the range $5.510^{-3}$ m/s and $1.110^{-8}$ m/s. An isotropic hydraulic conductivity was used in all performed simulations. All the model parameters used in the numerical study are presented in Table 1 and are based on those derived for kaolin clay, as used for the numerical studies of the CPTu in Mahmoodzadeh et al. (2014). The normalised penetration velocity $V$ is used to define the current drainage conditions for quasi-static penetration problems, as it enables the comparison between various test conditions. $V$ is defined as:

$$V = \frac{vd}{c_v} \tag{1}$$

where $v$ is the penetration rate, $d$ is the diameter of the CPT cone and $c_v$ is the vertical consolidation coefficient of the soil.

$$c_v = \frac{k_v(1+e_0)\sigma'_{v0}}{\lambda\gamma_w} \tag{2}$$

The normalised penetration velocity helps to correct for experimental scaling conditions by linking the penetration velocity and size of the object and soil volume (drainage lengths) to the properties of the soil such as the vertical effective stress $\sigma'_{v0}$, initial void ratio $e_0$, stiffness $\lambda$ and the hydraulic conductivity (via the vertical consolidation coefficient $c_v$).

DeJong & Randolph (2012) proposed a backbone curve of both the net cone resistance and excess porewater pressure normalised with the corresponding undrained value based on the result from seven different studies investigating the change in response for the CPTu under different drainage conditions and confining stress $p$. Mahmoodzadeh & Randolph (2014) also proposed a backbone curve based on a series of centrifuge test of CPTu penetration in kaolin clay. The net cone resistances are normalised with the results from the undrained penetration simulation and are presented in Figure 2. Whereas, the results for the normalised excess porewater pressure are presented in Figure 3. Both figures also show the two proposed backbone curves.

The transition of the simulated net cone resistance from the undrained to the intermediate and drained state are in good agreement with both backbone curves. The relative magnitude of the net cone resistance in the drained state, however, is considerably larger when compared to the proposed backbone curves. As this study is with equal strength in the soil as in the element near the interface, the contact between the CPTu and the soil can be considered rough. Monforte et al. (2021) performed an additional sensitivity study on the impact of the interface roughness on the CPTu simulations. The normalised net cone resistance for the rough interface ($\phi$ = 19) increased with about 40 % from the smooth interface (included in Figure 2). In contrast, the normalised excess porewater pressure response is not greatly affected by the interface formulation. Looking at Figure 2 the results from this study fit in between the smooth and the rough interface response reported by Monforte et al. (2021).

The normalised excess porewater pressure from this study is slightly shifted compared to the other studies (Figure 3). This is due to the presence of some numerically locked-in porewater pressures in a single element near the cone shoulder, i.e. at the $u_2$ position and is most prominent for very low hydraulic conductivities corresponding to a practically undrained state with normalised penetration velocities above 50. The porewater pressure presented herein, are unsmoothed and taken from the $u_2$ position and is considered to be accurate when looking at the relative change in response between the analyses in the sensitivity study.

## 4 CPTU IN SOFT CLAYS

The numerical investigation into the impact of soil properties on the CPTu penetration in soft (sensitive) clays was performed starting from a normally consolidated and isotropic reference state without

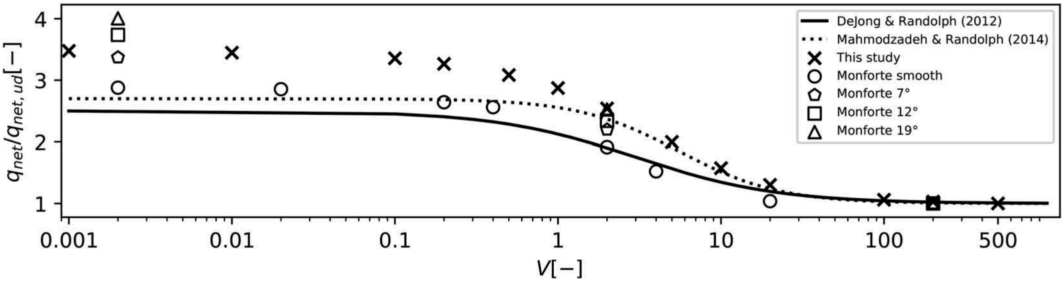


Figure 2. Normalised cone resistance over normalised penetration rate. Comparison between results from this study and Mahmoodzadeh & Randolph (2014) and DeJong & Randolph (2012). Results from Monforte et al. (2021) is included to indicate the effect of interface properties on the CPTu response.

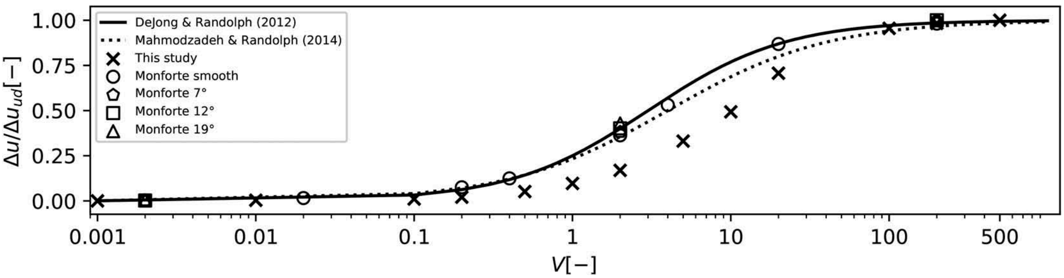


Figure 3. Normalised excess porewater pressure over normalised penetration rate. Comparison between results from this study and Mahmoodzadeh & Randolph (2014) and DeJong & Randolph (2012). Results from Monforte et al. (2021) is included to indicate the effect of interface properties on the CPTu response.

Table 2. Parameters used for investigation of the CPTu response in soft clays.

| Symbol | Parameter | Value |
|---|---|---|
| $OCR$ | Overconsolidation ratio [-] | 1.2, 1,5, 1,8 |
| $\chi_0$ | Initial amount of bonding [-] | 2, 5, 10, 20, 50 |
| $a$ | Rate of destructuration [-] | 6 |
| $b$ | Rate of destructuration due to to deviator strain [-] | 0.4 |
| $\alpha_0$ | Initial anisotropy [-] | 0.352 |
| $\omega$ | Rate of rotation [-] | 10 |
| $\omega_d$ | Rate of rotation due to deviator strain [-] | 0.374 |

initial bonding, using a normalised penetration velocity of $V$= 200 for the CPTu. First, the impact of $OCR$ on the soil response was investigated by increasing the $OCR$ in three increments from 1.02 to 1.8. The brittleness of the soil was also investigated by varying the SCLAY1S state parameter for destructuration $\chi_0$ between 0 (no initial structure) and 50 (clay with a high sensitivity). Although this parameter is closely related to the sensitivity of the soil it should not be considered to be similar. Finally, the impact of fabric anisotropy on the CPTu response was studied by introducing an initially inclined yield surface, that evolves with deviatoric and volumetric strains, in the model formulation. Table 2 presents the range of the SCLAY1S parameters used. The rate parameters and anisotropy $\alpha_0$ are assumed based on Gras et al. (2017) for natural clays, whilst keeping the original parameters from the kaolin clay. This ensures consistency of model parameters between simulations. Although this approach captures the soft soil features found in natural clays, the dataset does not represent a natural clay deposit.

Robertson (1990) proposed a classification system based on the normalised cone resistance $Q_t$ and pore pressure ratio $B_q$, where

$$Q_t = \frac{q_{net}}{\sigma'_{v0}} \tag{3}$$

$$B_q = \frac{\Delta u}{q_{net}} \tag{4}$$

The $Q_t$ is the relation between the net cone resistance from the CPTu measurements and the initial effective vertical stress. $B_q$ is the excess porewater pressure divided by the net cone resistance. This classification system is shown in Figure 4 with the results from the present numerical study. The arrows that annotate the data points correspond to each model parameter and are showing the direction of the normalised CPT response when the parameter is increased in the numerical analysis. Distinct trends for each parameter are clearly identified and are in good agreement with trends proposed by Robertson (1990), for both $S_t$ and $OCR$.

The numerical results are also presented in the classification chart (Figure 5) originally proposed by Schneider et al. (2008), which is based on $Q_t$ and the excess porewater pressure ($\Delta u$) normalised with the initial vertical effective stress ($\sigma'_{v0}$). The impact of changing $S_t$, $OCR$ and $c_v$ indicates clear trends that are in good agreement with the response suggested by Schneider et al. (2008). The effect of fabric anisotropy $\alpha$ only shows limited impact on the results. The results only slightly changed, due to the lower $Q_t$ and excess porewater pressures when compared to the isotropic model results.

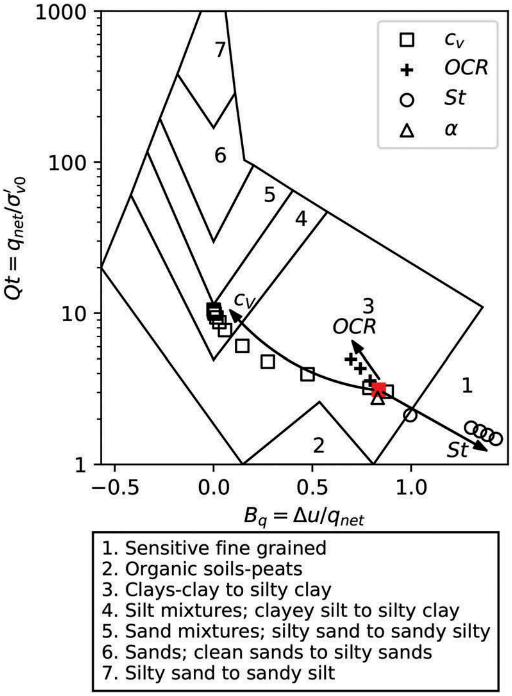


Figure 4. The effect on CPTu response from changing the consolidation coefficient $c_v$; overconsolidation ratio $OCR$; sensitivity $S_t$ and considering fabric anisotropy $\alpha$ in the characterisation chart for CPTu proposed by Robertson (1990).

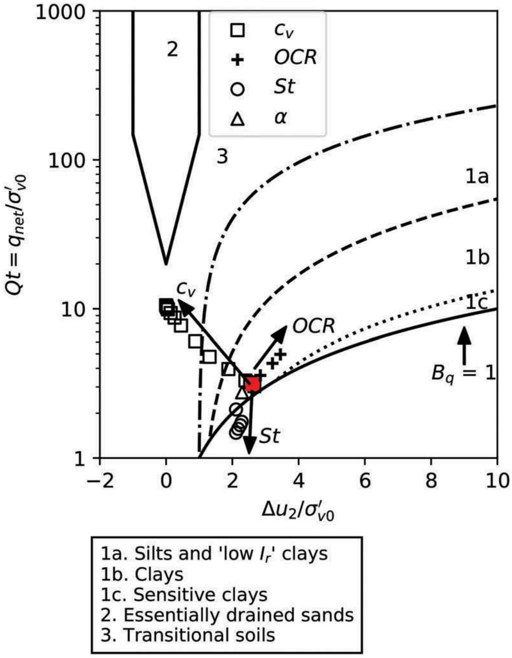


Figure 5. The effect on CPTu response from changing consolidation coefficient $c_v$; overconsolidation ratio $OCR$; sensitivity $S_t$ and considering fabric anisotropy $\alpha$ in the charaterisation chart for CPTu proposed by Schneider et al. (2008).

## 5 CONCLUSIONS

This paper presents the results from a series of CPTu simulations using a large deformation Finite Element framework in which partial consolidation during penetration is considered by linking the material deformations to the coupled response of porewater flow. An Eulerian framework, in which the mesh is fixed and the soil is able to move independently of the mesh, has been used, to avoid mesh distortions from large deformations associated with the CPTu penetration. The SCLAY1S model is implemented for these analyses, as it captures the evolving anisotropic strength-stiffness response, as well as the degradation of the initial bonding present in natural sensitive clays.

In the first part of the paper the effect of different drainage conditions is quantified and the overall trend compares well with prior work. Further studies need, however, to be conducted to improve the accuracy of the calculated porewater pressures at the shoulder of the CPTu. Extending the study to also include the response on the friction sleeve of the CPTu could further expand the conclusions of this study.

The impact of features that are fundamental to soft soils, i.e. hydraulic conductivity, $OCR$, sensitivity and anisotropy, on the CPTu response have been investigated in a hierarchical manner. The following can be concluded after integrating the results in the CPTu classification charts:

- Increasing the hydraulic conductivity leads to an increase in normalised penetration resistance while the normalised excess porewater pressure is decreasing.
- Increasing the $OCR$ is associated with an increase in both the normalised cone resistance and the normalised excess porewater pressure.
- Increasing $S_t$ leads to a considerable decrease in the normalised cone resistance while leaving the normalised excess porewater pressure nearly unaffected
- The simulated CPTu response is practically unaffected by soil anisotropy.

The conclusions of this study are in good agreement with suggestions from Robertson (1990) and Schneider et al. (2008) for the anticipated response from a change in $c_v$, $OCR$ and $S_t$. Hence, the results of this study contribute to the interpretation of the widely used classification charts, by linking it to the fundamental features of natural soils.

The extensive empirical evidence used to establish the relation between CPT and soil characteristics is in good agreement with the numerical results, increasing the confidence in the ability to accurately simulate penetration into soft soils with the proposed numerical method. Finally, the numerical simulations should be validated further against in-situ CPTu data.

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