Numerical simulation of CPTu under partially drained conditions

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ABSTRACT: Cone penetration testing (CPT) is a common and well-established in-situ investigation method. Thereby, soil properties are derived from the measured tip resistance, sleeve friction and pore water pressures using different correlations and good results for clays and sands, where undrained or drained behaviour governs the penetration process, are provided. However, the interpretation of CPT-data for intermediate soils, as they are typically found in Alpine basins in Austria, is difficult since partial drainage comes into play. In this work, the particle finite element method (G-PFEM) is used for the simulation of such a penetration problem in order to investigate partial drainage. CPT simulations were carried out considering different soil permeabilities showing a clear range for partially drained behaviour. Furthermore, it was found that the resulting qualitative pore pressure distribution strongly depends on the drainage condition and consequently pore pressure measurements at different positions (u_1, u_2, u_3) can be helpful for the interpretation of CPTu in intermediate soils.

1 Introduction

The characterization of soils is a fundamental part of every geotechnical project and forms the basis for the design. Conventional laboratory testing of soil specimens provides a wide range of parameters, however uncertainties due to recovery, transport and installation of the specimens remain a major influencing factor. Therefore, in-situ investigation methods are becoming an interesting alternative especially for the characterization of sensitive soils where sample disturbance is a major issue. Cone penetration testing (CPT) is a common method where a standard cone is pushed into the soil at a constant penetration velocity of 2 cm/s. Consequently, hydraulic and mechanical soil parameters are derived from the measured tip resistance, sleeve friction and pore pressure (for CPTu) based on well-established correlations. The latter proved to provide reliable results for clays and sands where undrained or drained system behaviour occurs during the penetration process. Thus, the interpretation of CPT in intermediate soils like silty or clayey sands is a difficult task as partial drainage governs the process. Modelling and understanding partial drainage during penetration is a challenging research topic whereby advanced numerical methods such as the Particle Finite Element Method (PFEM, see Oñate et al. 2011) allow to address the problem by numerical means. Of course, this kind of simulation is extremely complex since large displacements and deformations, highly non-linear material behaviour and the interaction between soil and cone need to be considered.

Studies by Sheng et al. (2014) and Ceccato & Simonini (2017) have been able to successfully model the penetration process under partially drained conditions. The present work aims to investigate partial drainage with regard to certain intermediate soils that are typically found in alpine basins in Austria.

2 Modelling CPT

The simulations are performed using the application G-PFEM (Monforte et al. 2017a, Monforte et al. 2017b) which has been developed within the Kratos framework (Dadvand et al. 2010) at the Polytechnic University of Catalonia (UPC) and the Center for Numerical Methods in Engineering (CIMNE).

2.1 Geotechnical-Particle Finite Element Method (G-PFEM)

Fundamentally, the quasi-static linear momentum and mass balance equations are solved using an updated Lagrangian formulation where the last known configuration at time t serves as integration domain for solving the current time step. According to the basic idea of PFEM the domain is represented by a cloud of nodes that carry all information and thus are treated as particles. At the beginning of a computation step the domain's boundaries are defined and nodes can be inserted in or deleted from critical areas before the mesh is built and standard FEM procedures are applied for solving the time step (Oñate et al. 2011). The frequent retriangulation of the domain avoids excessive mesh distortion and is essential for dealing with this kind of problems where large displacements and deformations occur as an ideally rigid cone penetrates the soil-water body. However, the remeshing comes with an increased computational cost and therefore linear shape functions for the nodal displacement ($\boldsymbol{u}$) and water pressure (p_w) fields in combination with a stabilized formulation are adopted. In this way the well-known problem of volumetric locking associated with low-order approximation of different physical quantities is addressed. In doing so, the nodal approximation of the determinant J of the deformation gradient – a measure for volumetric strain – is added as an additional degree of freedom leading to a $\boldsymbol{u}$-J-p_w formulation of the problem. The contact between rigid cone and deformable soil body is treated as a set of constraints to the solution and implemented using the penalty method. Moreover, a finite strain Modified Cam Clay (MCC) model based on the hyperelastic model by Houlsby is considered to describe the constitutive response of the soil.

More detailed information on the formulation and performance of G-PFEM as well as on the used elasto-plastic contact algorithm and the implemented Modified Cam Clay model is given in Monforte et al. (2017a) and Monforte et al. (2017b).

2.2 Basic model

An axisymmetric model is built consisting of a rectangular box measuring 1.1 m of height and 0.5 m of width. Initially, the cone is located at a depth of 0.1 m before penetration starts at a constant velocity *v* of 0.02 m/s. Standard cone geometry with the radius *R* of 1.78 cm and the tip angle of 60° is adopted. The domain's lower and lateral boundaries are fixed in perpendicular direction and free drainage is allowed except along the symmetry axis (see Fig. 1). A vertical load on top of the domain completes the model set up allowing to consider overburden pressure.

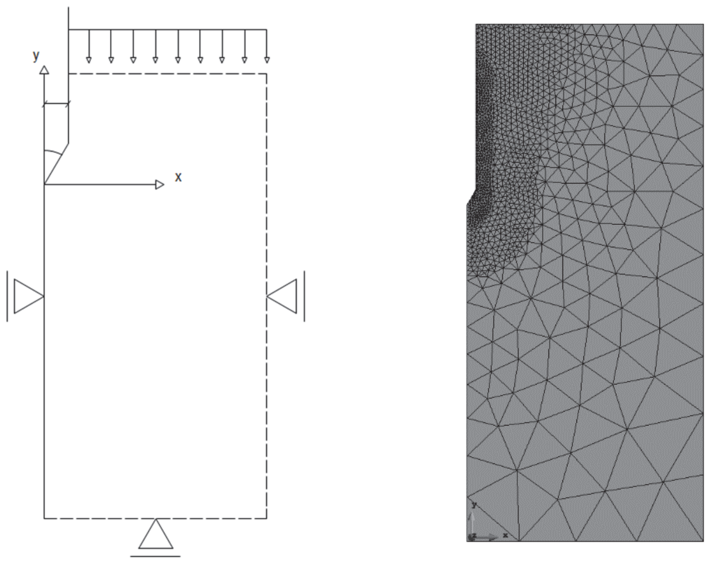

Fig. 1: Axisymmetric model (left) and refined mesh during the computation.

In order to investigate partially drained behaviour of postglacial silty deposits in Austria the present work considers the Salzburger Seeton, a typical silty soil from the region around Salzburg. The MCC parameters (see Tab. 1) are derived from the data of Sachsenhofer (2012) who evaluated and compared the results of in-situ CPTu and laboratory tests for the Seeton. Additionally, the effective overburden pressure of 130 kPa and the water pressure of 100 kPa act on top of the domain which corresponds to the in-situ stress level at a depth of around 13 m. This set up is the basis for the following simulations.

Tab. 1: MCC input parameters for Salzburger Seeton

ρ [kg/m³]	ρ_w [kg/m³]	λ^* [-]	κ^* [-]	φ' [°]	M [-]
1700	1000	0.015	0.005	22.5	0.88

G_0 [kPa]	α [-]	OCR [-]	p_{c0} [kPa]	K_w [kPa]	K_0 [-]
2900	0	1	100	$1*10^8$	0.7

3 Simulation results

The aim of the present work is to simulate cone penetration in Salzburger Seeton for different permeabilities ($2 \cdot 10^{-9}$ to $2 \cdot 10^{-5}$ m/s) and thereby focus on the evolution of the pore pressure. All examined test cases consider a smooth interface between cone and soil. Fig. 2 shows the normalized depth-profiles of the tip resistance q_c and the pore pressure measured in the middle of the cone (u_1), at the cone shoulder (u_2) and on top of the friction shaft (u_3). The measured quantities reach a stationary level after an initial penetration of around 4 to 6 radii.

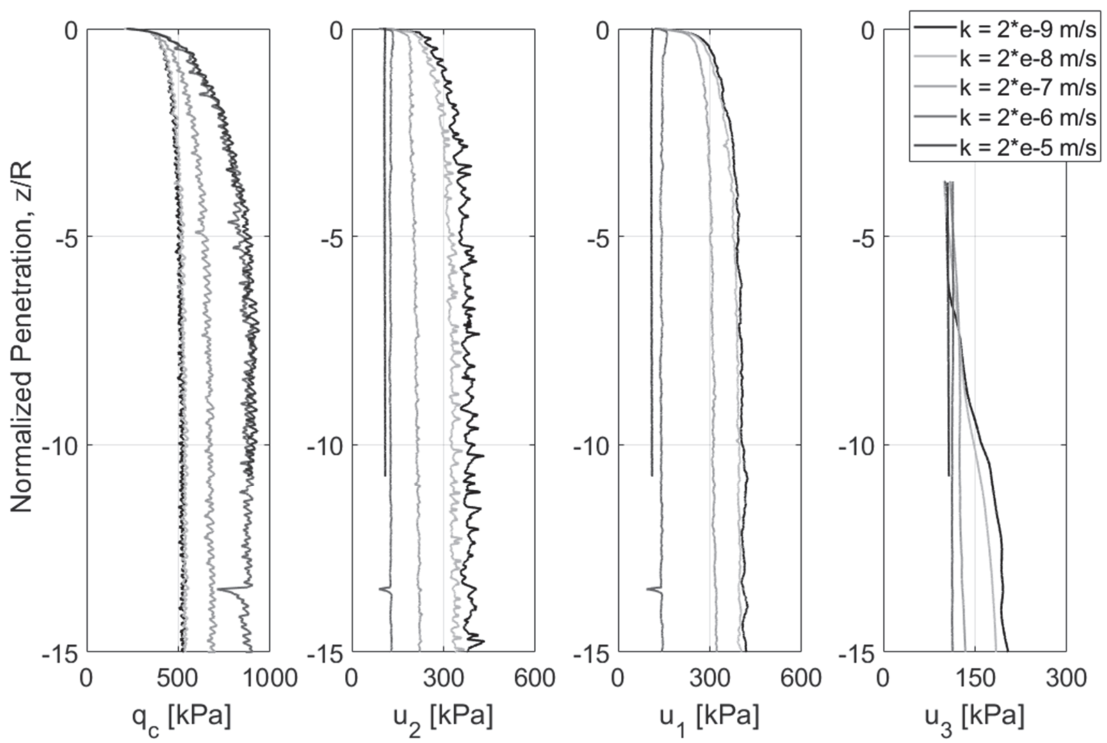

Fig. 2: CPTu profiles for tip resistance q_c and pore pressure u_1, u_2 and u_3 for permeabilities ranging between $2 \cdot 10^{-9}$ and $2 \cdot 10^{-5}$ m/s.

As expected, the lowest permeability of $2 \cdot 10^{-9}$ m/s leads to the lowest q_c and the highest values of u_1, u_2 and u_3. Consequently, a stepwise increase of k until reaching a value of $2 \cdot 10^{-5}$ m/s results in an increase of q_c and a decrease of the pore pressure. Ideally, constant values for undrained and drained behaviour are reached once k becomes low or high enough respectively. This trend is also apparent from the results in Fig. 2 indicating on one hand the onset of undrained behaviour as k tends towards $2 \cdot 10^{-9}$ m/s and on the other hand drained behaviour as k tends towards $2 \cdot 10^{-5}$ m/s. Of course, ideal drained or undrained behaviour is not reached within the present set of calculations but the partially drained regime, which is of primary interest, appears to be covered.

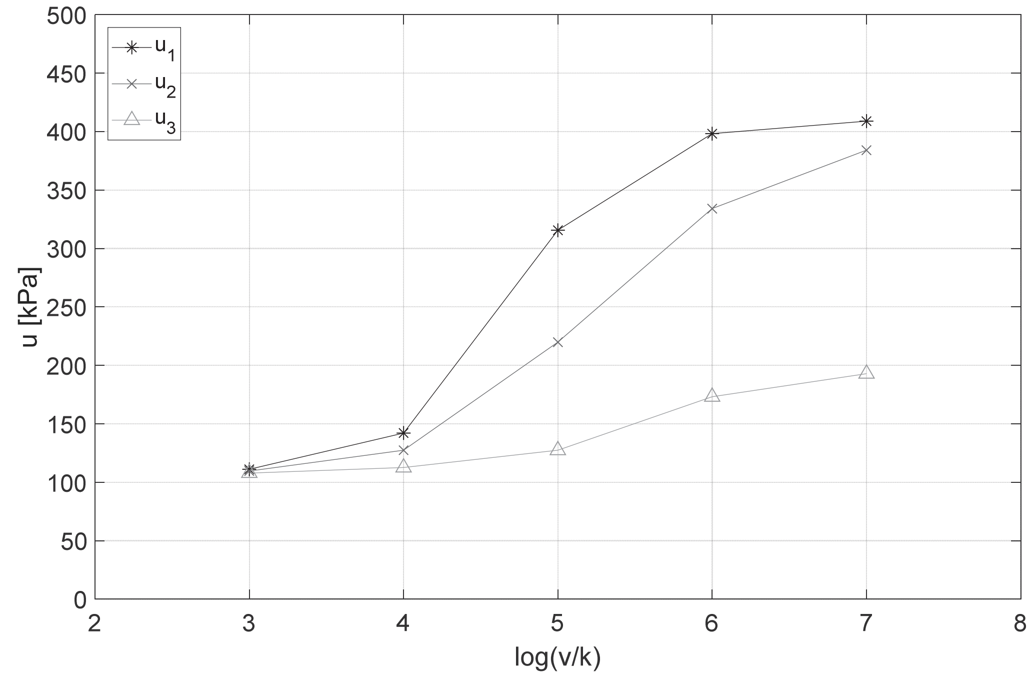

Fig. 3: Pore pressure measured at u_1, u_2 and u_3 positions versus normalized penetration rate.

Furthermore, the stationary averages of u_1, u_2, u_3 are calculated between 12 and 13 radii of penetration depth and plotted over the normalized penetration rate *v/k* as introduced by Sheng et al. (2014) in Fig. 3. Note that the mean values for the test case with $2 \cdot 10^{-5}$ m/s are obtained through extrapolation since the computation crashed before reaching the reference depth. In any case, a stationary level is reached (see Fig. 2), also for the u_3 position. Again, the transition from undrained towards drained behaviour is observable for all 3 curves and the basic character of the curves is the same. However, the specific shapes differ clearly for the respective measurement positions u_1, u_2, u_3. This appears reasonable when considering the pore pressure distribution around the penetrating cone for different permeabilities (see Fig. 4). Changing drainage conditions do not only affect the maximum pore pressure but also its location with respect to the cone. For the undrained case (a), the centre of the excess pore pressure bulb is located right around the cone and extends far beyond the cone shoulder. Thus, the measurements at the u_1 and u_2 positions are close to the maximum pore pressure. On the other hand, case (b) considers an increased permeability of $2 \cdot 10^{-6}$ m/s leading to lower overall pore pressures and to a different distribution around the cone. Generally, the pressure bulb moves further downwards and is now located at the tip of the cone. Consequently, the pressure at u_1 is the closest measurement to the maximum pore pressure whereas u_3 is almost giving the initial in-situ pressure.

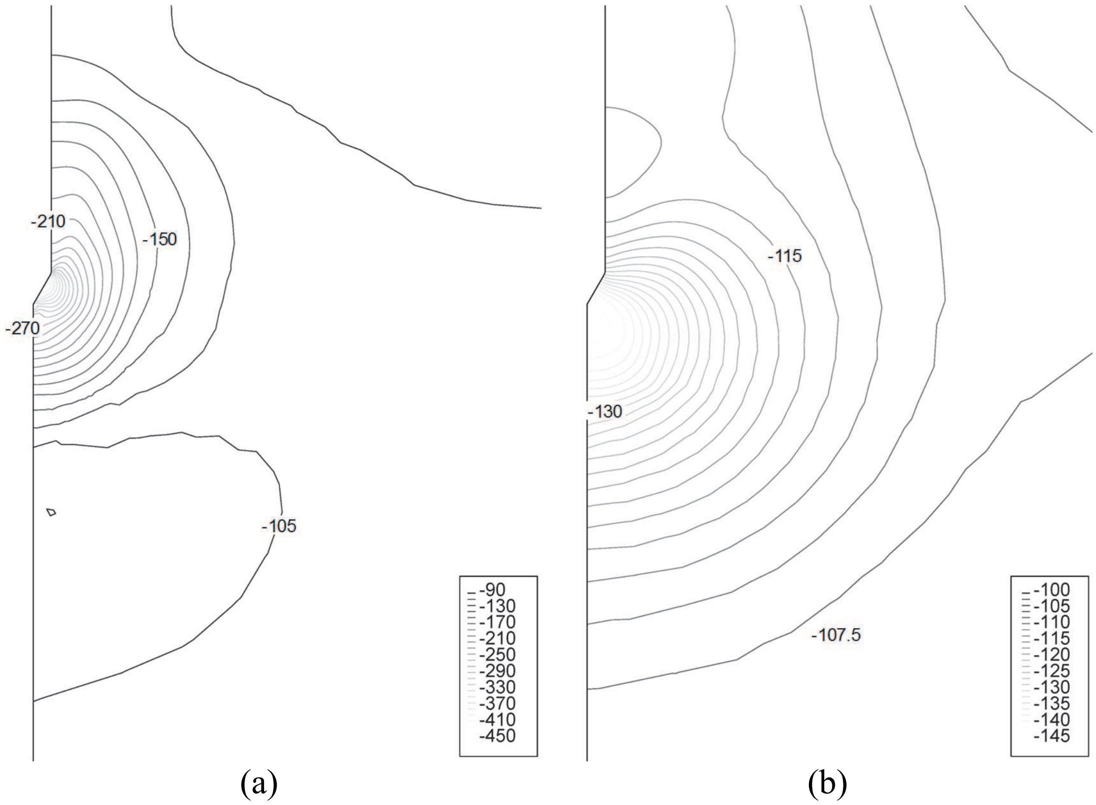

Fig. 4: Pore pressure fields after 11 radii of penetration for $k = 2 \cdot 10^{-8}$ m/s (a) and $k = 2 \cdot 10^{-6}$ m/s (b).

The different measurement positions appear to be a possible explanation for the different shapes of the curves in Fig. 3. Therefore, the consideration of multiple measurement locations for the pore pressure – in practice only the u_2 pressure at the cone shoulder is recorded during most CPTu – can be an interesting approach when dealing with partial drainage as changing ratios between u_1, u_2 and u_3 are an indicator for the observed change in pore pressure distribution associated with partial drainage.

4 Conclusion

The present work is part of the ongoing research dealing with cone penetration under partially drained conditions. The numerical approach based on the PFEM is promising as it allows to simulate the whole penetration process. This has been done for different permeabilities where partially drained behaviour was observed. Furthermore, the qualitative distribution of the pore pressure during penetration was studied suggesting that measurements at different positions (u_1, u_2, u_3) can be helpful for the interpretation of CPTu investigations under partial drainage.

5 Literature

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