Study of the effect of drainage conditions on cone penetration with the Material Point Method

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Abstract. Cone Penetration Testing (CPT) is a widely used in situ soil testing technique which allows to estimate soil stratigraphy and various soil parameters. Depending on the soil's consolidation coefficient, undrained, partially drained or drained conditions might occur. Partially drained conditions are commonly encountered in soils such as silt and sand-clay mixtures. Correlations between CPT measurements and soil properties are usually only valid for fully drained or fully undrained conditions which may lead to inaccurate estimates of the properties of silty soils. This paper aims at improving the understanding of the penetration process in different drainage conditions through advanced numerical analyses. A two-phase Material Point Method is applied to simulate the large soil deformations and the generation and dissipation of excess pore pressures that occur during penetration. The constitutive behavior of the soil is modelled with the Modified Cam Clay model. The implemented MPM formulation is validated by comparing numerical results with the results of centrifuge tests under different drainage conditions.

Keywords. CPT, MPM, site investigation, numerical modelling, partially drained conditions, multiphase formulation.

1. Introduction

Standard Cone Penetration Testing (CPT) consists in pushing a measuring device with a conical tip into the ground with a constant velocity of 2 cm/s. From the measurements of tip resistance (q_c) and sleeve friction (f_s) various soil properties, such as the friction angle, the undrained shear strength and the compression index, can be estimated; see for example Ref. [1].

When performing CPT, different drainage conditions might be encountered depending on the soil's consolidation coefficient. In highly permeable soils, such as sand, fully drained conditions occur: negligible excess pore pressures build up around the tip and quickly dissipate. In nearly impermeable soils, such as clay, fully undrained conditions occur: considerable excess pore pressures are generated that dissipate at a much slower rate than the penetration velocity. In soils such as silt, partially drained conditions are encountered: excess pore pressures dissipate to some extend in the vicinity of the cone during its penetration.

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If the pressure dissipation rate is relatively high compared to the penetration rate, the soil in the vicinity of the advancing cone consolidates during penetration. Effective stresses increase, resulting in larger shear strength and stiffness compared to undrained conditions and subsequently higher tip resistance and sleeve friction [2].

Most of the empirical and theoretical correlations commonly used to estimate soil properties are not valid for partially drained conditions. This may lead to an inaccurate estimate of soil properties.

This paper investigates the effect of the drainage condition on the cone resistance in soft soils through numerical analyses. For this purpose, a fully coupled two-phase Material Point Method (MPM) featuring a contact formulation for modeling soil-structure interaction is applied. The method is described in Section 2. The soil response is simulated with the Modified Cam Clay (MCC) model [3].

To the authors' knowledge, a numerical study of CPT which considers the three-dimensional large deformations, the roughness of the penetrometer surface as well as non-linear soil behaviour in a wide range of drainage conditions is a novelty. Indeed, previous numerical studies [4, 5] could not consider all these important aspects.

In Section 3 the numerical simulation of cone penetration is presented, followed by the results in Section 4. The paper ends with concluding remarks and suggestions for future research (Sec. 5).

2. The two-phase Material Point Method

The MPM has been developed for large deformation problems in solid mechanics [6] and was first applied to granular materials by Więckowski [7, 8] and Coetzee et al. [9]. It has been used successfully in the study of numerous geomechanical problems; amongst others anchor pull-out [9], dam failure [10], landslides [11], cone penetration [12], and pile installation [13].

With the MPM, arbitrary large deformations of a body are simulated by material points (MP) moving through a finite element mesh. The MP carry all the information of the continuum such as velocity, acceleration, stress, strain, material parameters as well as external loads. The finite element mesh is used to solve the equations of motion for each time step, but does not store any permanent information.

At the beginning of each time increment, information is mapped from the MP to the nodes of the mesh. The governing equations are solved identically to the classical Updated Lagrangian Finite Element methods. Strains, stresses and other state variables

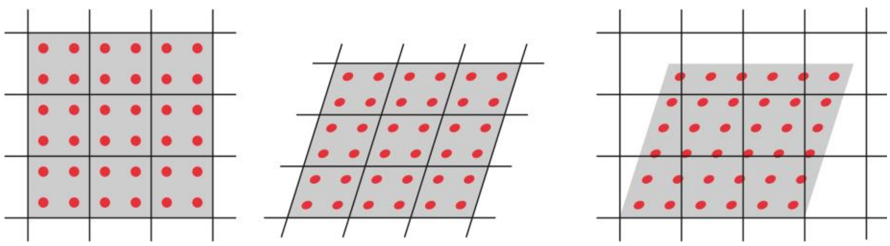


Figure 1. (left) configuration at the beginning of a time step in which the red dots are the MP; (center) incrementally deformed mesh; (right) reset mesh at the end of a time step

at the MP as well as the updated position of the MP are computed from the obtained nodal accelerations. Once information is mapped from the nodes to the MP, the mesh is usually reset to its original state, though it could also be adjusted or entirely redefined. Figure 1 illustrates the computation steps of a time step with the MPM.

The finite element grid must extend across the entire region of space through which the material is expected to move. However, only nodes attached to finite elements that contain material points (active elements) are considered when setting up the equilibrium equations.

An available 3D MPM with explicit time integration is used in this study. Despite specifically developed for dynamic problems, it is also well suited for the analysis of the considered quasi-static CPT problem as described below.

The generation and dissipation of excess pore pressure is simulated with a fully coupled two-phase formulation [14]. The equilibrium equations are solved for the accelerations of soil skeleton and water phase as primary unknown variables as presented in [15].

The soil-cone interaction is modelled with a contact formulation specifically developed for the MPM [16], which is based on the Coulomb's friction law. The advantage of this algorithm is that it detects the contact surface automatically and does not require any special interface elements. It is proved to be efficient in modeling interaction between solid bodies as well as shearing in granular materials [9, 17].

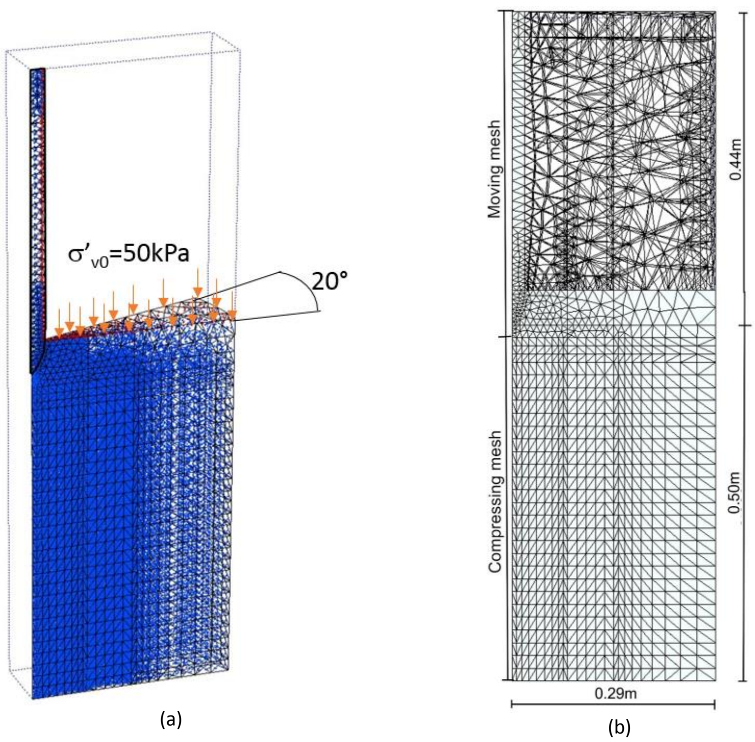


Figure 2 Geometry and discretization of the CPT problem.

Table 1 Material parameters of numerical analyses

Parameter	Symbol	Value
Virgin compression index [-]	λ	0.205
Recompression index [-]	κ	0.04
Effective Poisson's ratio [-]	ν'	0.25
Slope of CSL on p-q plane [-]	M	0.92
Bulk modulus of the water [kPa]	K_w	36600
Initial void ratio [-]	e_0	1.41
Saturated density [kg/m^3]	ρ_{sat}	1700

3. The numerical model

Taking advantage of the rotational symmetry of the cone penetration problem, only a 20° slice is considered. The cone is slightly rounded in order to circumvent numerical problems induced by a discontinuous edge at the base of the cone. Apart from this modification, the dimensions of the penetrometer correspond to those of a standard penetrometer: the apex angle is 60° and the cone diameter (D) is 0.036m.

The size and the refinement of the mesh have been determined through preliminary calculations as a compromise between computational cost and accuracy. It extends 8D in radial direction and initially 14D below the tip. It counts 13 221 tetrahedral elements. 105 634 material points are located in the initially active elements. Figure 2 shows the geometry and discretization of the CPT problem.

At the lateral mesh surfaces displacements are constrained in normal direction while the bottom of the mesh is fully fixed. For the water phase, the radial boundaries are impermeable since they correspond to symmetry axes of the problem while the bottom and the circumferential boundaries are permeable.

In order to maintain a refined mesh always around the cone, a special procedure, called moving mesh, is adopted [18]. It consists in adjusting the part of the mesh adjacent to the penetrometer (Fig. 2b) to the movement of the cone after each time step. This ensures that the penetrometer surface coincides with element boundaries. The elements of this zone keep the same shape throughout the computation, while the elements in the compressed zone below the cone (Fig. 2b) reduce their vertical length. The discretization of the compressed zone is defined in such a way that the elements keep a reasonable aspect ratio throughout the analysis.

The material weight is neglected because the gradient of the vertical effective stress is negligible compared to the stress level developed during the penetration. The initial vertical and horizontal effective stresses are 50kPa and 34kPa respectively. A vertical stress of 50kPa is applied at the top surface of the soil simulating an initial position of the cone at about 5m depth. The clay is considered normally consolidated. A further penetration by 10D is simulated.

The input parameters for the MCC model are summarized in Table 1; they are typical of kaolin clay, which is a material often used in laboratory tests, thus allowing a comparison with experimental evidence.

The variation of drainage conditions is usually achieved in experimental investigations by varying the penetration velocity v. In this study the variation of drainage is obtained by changing the permeability k, while keeping $v = 0.02m/s$.

Although the complete range of drainage conditions can be simulated with the two-phase formulation, fully drained and fully undrained conditions are simulated in a simplified way considering the soil as a one-phase material, thus reducing the computational effort. In fully drained conditions the presence of the water is neglected. In fully undrained conditions there is negligible relative movement between solid and water; therefore the equilibrium of the soil-water mixture is considered rather than the equilibrium of soil and water as separate phases. The excess pore pressure increment is computed multiplying the volumetric strain by the bulk modulus of the water [19].

In this study, the soil-cone interface is characterized by a friction coefficient of 0.3. Reasonable values of the friction coefficient for low plasticity clay in contact with steel lie between 0.2 and 0.35 [20].

4. Results

The dependence upon the drainage conditions can be expressed through the normalized penetration rate introduced by Finnie and Randolph [21]:

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

where v is the penetration velocity, D the cone diameter and c_v the soil's consolidation coefficient, which can be estimated according to [22] with:

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

where k is Darcy's permeability, σ'_{v0} is the initial vertical effective stress, γ_w=10kN/m^3 is the water unit weight.

Figure 3 shows how the tip stress increases with the vertical displacement of the cone for different drainage conditions. The steady state tip stress, which corresponds to the tip resistance q_c, is reached after a displacement of about 6D. As expected the tip resistance increases with decreasing V, i.e. moving from undrained to drained conditions. In case of V = 1.2 the tip resistance is 7% lower than for drained conditions, and in case of V = 12 the tip resistance is 5% higher than for undrained conditions.

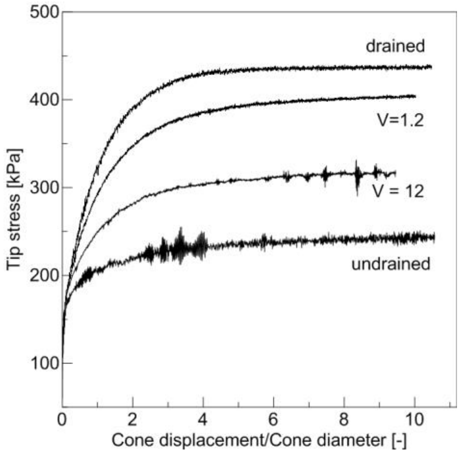


Figure 3 Tip stress over normalized cone displacement for different drainage conditions.

The excess pore pressure distributions are shown in Figure 4. Approximately undrained behavior is observed for V = 12 at which the pore pressure is about 150kPa. On the contrary, for V = 1.2 the behavior is nearly drained and the pressure is about 30kPa.

Figure 5 shows the deviatoric stress distributions for four of the performed analyses. The shear strength and the stiffness of the soil increase with decreasing the normalized penetration rate because of pore pressure dissipation and subsequent increase of effective stress. The lowest deviatoric stress around the cone is observed in undrained conditions (Fig. 5a), which corresponds to the undrained shear strength of the soil. In partially drained conditions, it is about 45kPa in case of V=12 (Fig. 5b) and 90kPa in case of V=1.2 (Fig. 5c). The highest deviatoric stress, about 120kPa, is encountered in drained conditions (Fig. 5d).

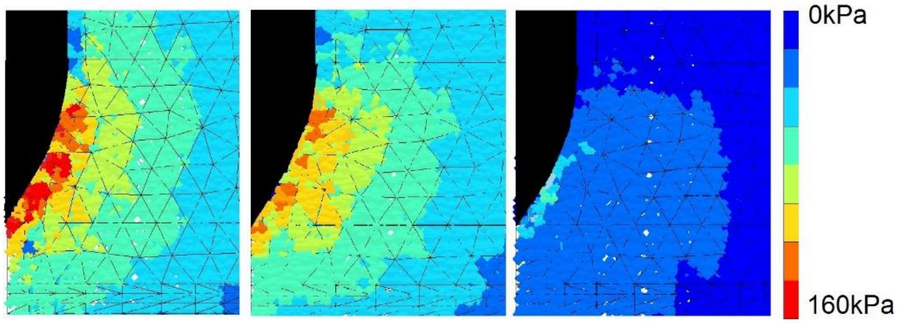
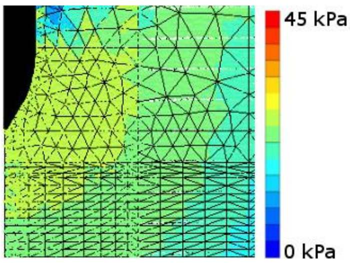
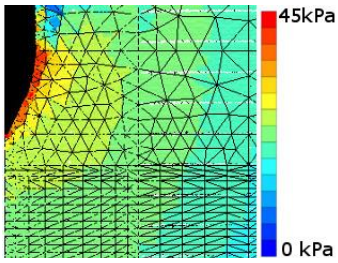


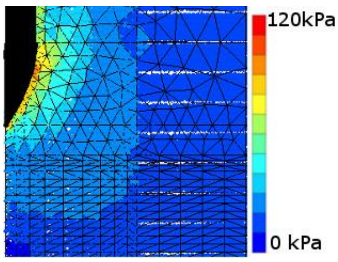
Figure 4 Excess pore pressure in case of undrained conditions (left) and partially drained conditions for V=12 (center) and V=1.2 (right).



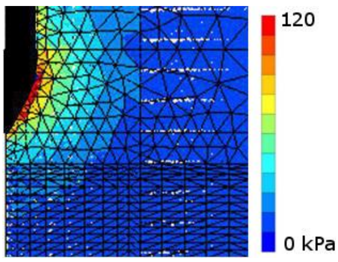
(a)



(b)



(c)



(d)

Figure 5 Deviatoric stress in case of undrained conditions (a), partially drained conditions with V=12 (b), partially drained conditions with V=1.2 (c) and drained conditions (d)

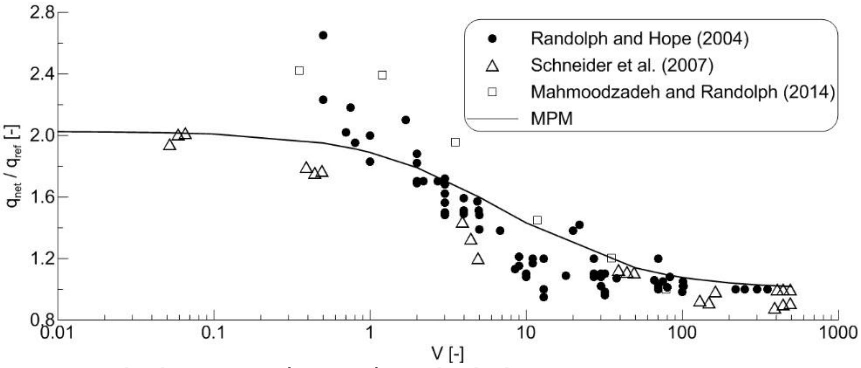


Figure 6 Normalized resistance as function of normalized velocity

The net resistance for a generic value of the normalized velocity V, $q_{net} = q_c - \sigma'_{v0}$, can be normalized by dividing it by the undrained net tip resistance, $q_{ref} = q_{c,und} - \sigma'_{v0}$ where $q_{c,und}$ is the undrained net tip resistance. Figure 6 shows the normalized resistance plotted over the normalized velocity and compares the numerical results with experimental data on kaolin [22-24]. Numerical results agree well with experimental data; differences can be attributed to uncertainties in the estimation of the input parameters for the soil model. The normalized resistance is constant and equal to 2.1 for drained conditions (V<0.1). Undrained conditions are observed for V>200.

5. Conclusions

This paper shows the capability of the two-phase MPM using a contact formulation and the MCC model to simulate the complex problem of cone penetration under different drainage conditions. The effect of drainage conditions has been studied through the variation of the normalized penetration rate.

The cone resistance increases with decreasing normalized penetration velocity because the soil near the advancing cone consolidates, thereby developing larger shear strength and stiffness. Indeed, as the penetration velocity decreases, the deviatoric stress increases and the pore pressure decreases. Numerical results are in good agreement with experimental evidence.

To further improve the understanding of CPT, the MPM will be used to analyze the effect of cone roughness, material parameters, and initial stress state on the cone tip resistance.

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