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Two-phase Material Point Method applied to the study of cone penetration

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ABSTRACT

This paper presents numerical simulations of Cone Penetration Test (CPT) in water-saturated soft soils taking into account pore pressure dissipation during installation. Besides modelling interaction between soil skeleton and pore fluid, the problem involves large soil deformations in the vicinity of the penetrometer, soil–structure interaction, and complex non-linear response of soil. This makes such simulations challenging. Depending on the soil's permeability and compressibility, undrained, partially drained or drained conditions might occur. Partially drained conditions are commonly encountered in soils such as silts and sand–clay mixtures. However, this is often neglected in CPT interpretation, which may lead to inaccurate estimates of soil properties. 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 large soil deformations and generation and dissipation of excess pore pressures during penetration. The constitutive behaviour of soil is modelled with the Modified Cam Clay model. Numerical results are compared with experimental data showing good agreement.

1. Introduction

The cone penetration test (CPT), or the more advanced piezocone penetration test (CPTU), consists in pushing a measuring device with a conical tip into the ground with a constant velocity of 2 cm/s. From the derived measurements of tip resistance q_c, sleeve friction f_s, and pore pressure u various soil properties as well as the soil stratigraphy can be estimated [1].

Depending on the soil's permeability, different drainage conditions might be encountered at the standard penetration rate. Drained conditions occur in highly permeable soils such as sand, i.e. negligible excess pore pressures are generated and immediately dissipate. Undrained conditions occur in nearly impermeable soils such as clay, i.e. significant excess pore pressures build up around the cone, but their dissipation is negligible. In soils such as silt, silty sand and clayey sand, the cone penetrates in partially drained conditions, i.e. part of the generated excess pore pressures dissipate nearby the advancing cone.

Most of the existing empirical and theoretical correlations between CPT measurements and soil properties do not consider the occurrence of partially drained conditions. Field data is interpreted assuming drained or undrained conditions. This leads to inaccurate estimates of geotechnical parameters for the soils in which the cone penetrates in partially drained conditions. A better understanding of the penetration process will allow a more accurate interpretation of CPT and thus more economic and reliable engineering solutions. The purpose of this paper is to study the effect of the drainage conditions on the measured tip resistance by means of advanced numerical analyses.

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, thereby developing larger shear strength and stiffness compared to undrained conditions, thus resulting in higher tip resistances [2].

The problem has been mainly studied experimentally; see e.g. [3–7]. To the authors' knowledge, a numerical study of CPT, which considers the three-dimensional large soil deformations, the roughness of the penetrometer as well as non-linear soil behaviour in a wide range of drainage conditions, is a novelty. Previous numerical studies assumed drained conditions [8–14], or undrained conditions [15–20].

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Abu-Farsakh et al. [21] were the first to investigate the effect of permeability on the generated excess pore pressure and its subsequent dissipation, but they did not consider the effect of partial consolidation on the tip resistance. More extensive numerical studies of the effect of drainage conditions on CPT measurements were performed by Silva et al. [22] and Yi et al. [23]. Silva et al. studied horizontal stress and pore pressure distributions varying the penetration velocity. In their approach, based on the cavity expansion theory coupled with Finite Element Method, only radial soil deformations and water flow are considered. Soil behaviour is modelled with the modified Cam Clay model. Yi et al. performed interesting parametric analyses using the Updated Lagrangian Finite Element method with logarithmic strain. However, they encountered numerical problems related to severe mesh distortions, which had to be controlled by remeshing. The soil–cone interaction is simulated with a couple of frictionless interfaces because numerical difficulties were encountered including friction. The Drucker-Parger model is applied in their study; despite it is recognized to be not suitable to simulate soil response in undrained conditions. Partial drainage was also considered in pile installation problems by Hamann et al. [24]. They applied the Coupled Eulerian–Lagrangian (CEL) approach to the simulation of the pile jacking process in sand, whose constitutive behaviour is determinded by the hypoplastic model.

The Material Point Method (MPM) is adopted in this study to simulate large deformations of soil during cone penetration. Generation and dissipation of pore pressures are taken into account by the recently implemented two-phase formulation [25], which considers the equilibrium of the solid and water as separate phases. A dynamic 3D formulation with semi-explicit time integration scheme is used; however, quasi-static problems, such as CPT, can be simulated with it as well.

The software was originally developed at the University of Stuttgart by the research group of Prof. P.A. Vermeer with the aim of introducing MPM in geotechnical engineering. At present it is under development by a research community including Deltares (Delft, The Netherlands), University of Cambridge (UK), University of Catalunya (Barcelona, Spain), TU Hamburg–Harburg (Germany), University of Padua (Italy), TU Delft (The Netherlands). It implements an enhanced version of the original MPM proposed by [26], which has been extensively validated for geomechanical problems [12,27–31].

This study examines the cone penetration in a homogeneous soft soil subjected to an anisotropic geostatic stress state considering the whole range of drainage conditions, i.e. from fully undrained to fully drained. To take into account the elasto-plastic soil response, the soil behaviour is simulated with the Modified Cam Clay model [32].

The soil–cone interaction is modelled with the contact formulation proposed by Bardenhagen et al. [33]. This formulation was originally developed for one-phase analyses; it has been extended to the two-phase formulation in the frame of this study in order to take into account the interaction between the water phase and the impermeable probe.

The results of the numerical study on the effect of the drainage conditions are compared with previous numerical results and experimental data showing good agreement.

2. The Material Point Method for saturated soil

2.1. Overview of the Material Point Method

The classical Updated Lagrangian Finite Element method (UL-FEM) has been successfully used for decades in geomechanics. However, difficulties appear when applied to large deformation problems because of issues with element distortions. The need to overcome this drawback led to the development of alternative methods such as the Discrete Element method (DEM) [34], the Smoothed Particle Hydrodynamic (SPH) [35] and the MPM [26].

MPM belongs to the family of particle-based methods. It derives from the Particle-in-cell method (PIC) used in fluid mechanics [36]. Schreyer, Sulsky and co-workers, extended it for problems involving history-dependent materials [26]. It was first applied to granular materials by Więckowski [37,38] and Coetzee [39]. This method has been successfully used in the study of a number of geomechanical large deformation problems such as anchor pull-out [40], landslides [41], cone penetration [18] and pile installation [42]. The development of multiphase formulations is recent [25,43,44]. These formulations have been applied to the study of shallow foundations, retaining walls [45], dam collapse [46] and riverbank failure [47].

In MPM, large deformations of a body are simulated by the movement of a set of material points (MPs) through a computational finite element mesh. The MPs carry all the information of the continuum such as density, velocity, acceleration, stress, strain, material parameter as well as external loads. It can be regarded as an extension of FEM, because the underlying finite element grid is used, like in FEM, to solve the system of equilibrium equations for each time increment [48]. However, in an additional step, information is mapped from nodes to MPs. The mesh does not follow the deformations of the body as in the FEM, thus preventing problems of element distortion.

Fig. 1 summarizes the computational steps of the MPM solution procedure, which is explained in the following. Let us consider a one-phase dynamic problem governed by the discretized momentum equation:

$$\boldsymbol{M}\dot{\boldsymbol{v}} = \boldsymbol{F}^{ext} - \boldsymbol{F}^{int} \quad (1)$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{v}$ is the velocity, $\boldsymbol{F}^{ext}$ is the external load and $\boldsymbol{F}^{int}$ is the internal load. The superposed dot $(\dot{\ })$ indicates the material time derivative. Eq. (1) is derived from the weak form

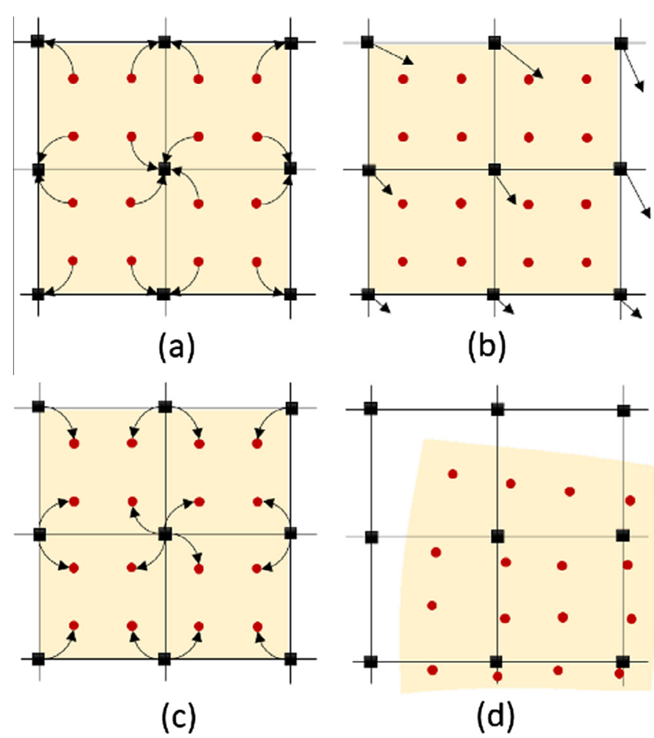

Fig. 1. Computation scheme of MPM: (a) interpolate state variables to the grid nodes; (b) solve the governing equations of motion at the nodes; (b) update MP velocity, stress, strain and other state parameters; (c) update MP housekeeping.

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