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Research Paper

Discrete modeling of penetration tests in constant velocity and impact conditions

Quoc Anh Tran, Bastien Chevalier *, Pierre Breul

Clermont Université, Université Blaise Pascal, Institut Pascal, BP 10448, F-63000 Clermont-Ferrand, France
CNRS, UMR 6602, Institut Pascal, F-63171 Aubière, France

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ABSTRACT

The paper presents investigations on the penetration tests in granular material. A discrete numerical study is proposed for the modeling of penetration tests in constant velocity conditions and also in impact conditions. The model reproduces qualitatively the mechanical response of samples of granular material, compared to classical experimental results. Penetration tests are conducted at constant velocity and from impact, with similar penetration rates ranging from 25 mm s^{-1} to 5000 mm s^{-1}. In constant velocity condition, the value of tip force remains steady as long as the penetration velocity induces a quasi-static regime in the granular material. However, the tip force increases rapidly in the dense flow regime corresponding to higher penetration rate. Impact tip force increases with the impact velocity. Finally, the tip forces obtained from impact penetration tests are smaller compared to the one obtained in constant velocity conditions in both quasi-static and dense flow regimes.

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1. Introduction

In the field of in situ mechanical characterization of soils, penetration tests are commonly used. The tip resistances, deduced from pile driving theory, can be measured either in dynamic (q_d) (Fig. 1) or in static conditions (q_c).

Recently, the measurement technique in impact conditions was improved. It is now possible to record the real-time response of the soil during one impact in terms of tip force and penetration distance [1,2] (Fig. 2). Mechanical properties other than the classical tip resistance might be extracted from this new kind of experimental measurements. Recent studies from [3,4] showed the interest in penetration tests for the characterization of coarse material.

Penetration tests generate large deformations and a highly non-homogeneous solicitation, Discrete Element Method (DEM) is then a particularly relevant numerical method to model this test. Many authors proposed numerical models for reproducing penetration tests in static conditions i.e. in constant velocity conditions in 2D [5–10] and in 3D [1,4,11,12]. However, [1,13,14] showed that tip resistance depends on the loading type used in the penetration process. Very few researches focus to the modeling of penetration tests in impact conditions.

In this paper, we propose a numerical model of penetration tests using DEM for reproducing tests in both constant velocity and impact conditions in coarse materials. The penetration device modeled here is a light penetrometer [3,4]. Macroscopic results are discussed in this paper. After the description of the numerical model, we present the effect of penetration rate on the tip force obtained from both constant velocity and impact penetration tests will. Finally, a comparison of the tip force obtained with both loading types is proposed and discussed.

2. Numerical model

Discrete Element Method in two dimensions was used with Itasca's software PFC^{2D} [15]. Table 1 summarizes the parameter of the model. Granular material samples of 10,000 cylindrical particles were generated and tested in a rectangular box (Table 1). A diameter ratio of 2 was chosen between largest and smallest particles. The average particle diameter of the material D_p is equal to 5.4 mm (Fig. 3).

The sample preparation broke down into 3 steps. First, a frictionless particle radius expansion method without gravity was used in order to reach a minimum value of sample porosity of $n = 0.15$. Secondly, the final value of friction coefficient of $\mu_{particle} = 1.00$ was applied as well as the gravity. We conducted simulations with different values of particle friction and found no influence of particle friction on the results for values of

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* Corresponding author at: Institut Pascal, CNRS, UMR 6602, F-63171 Aubière, France. Tel.: +33 (0)4 73 40 75 23; fax: +33 (0)4 73 40 74 94.

E-mail address: bastien.chevalier@univ-bpclermont.fr (B. Chevalier).

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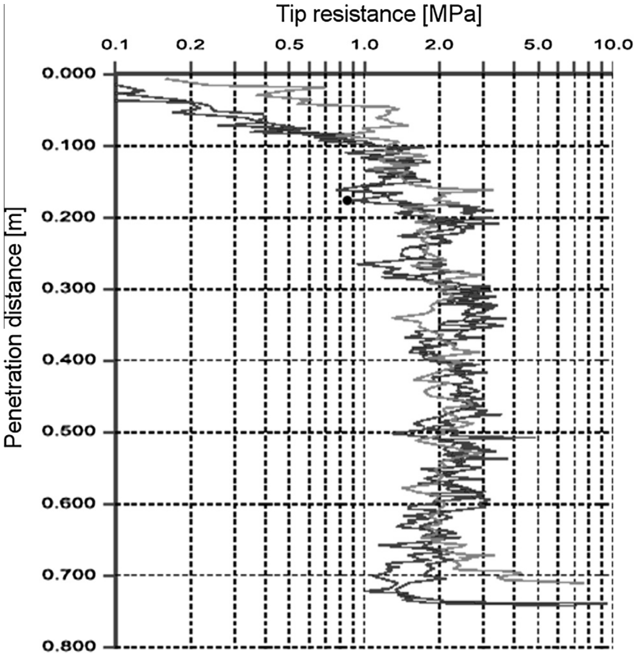

Fig. 1. Example of an experimental result of a impact penetration test.

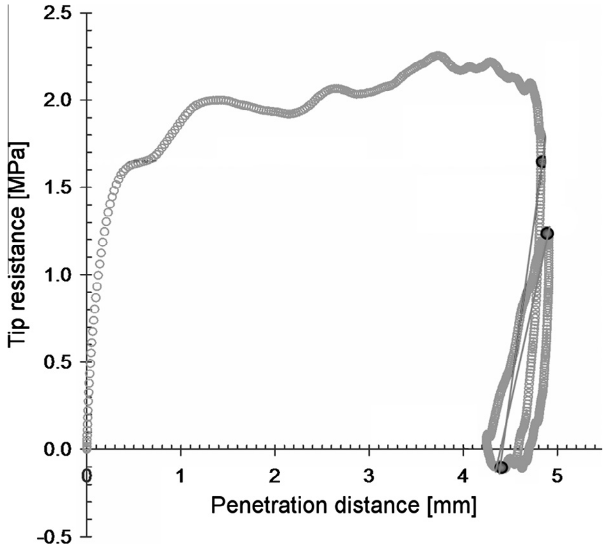

Fig. 2. Example of experimental load–penetration curve obtained in a impact penetration test for one impact [2].

$\mu_{particle} \geqslant 0.50$. So the value of $\mu_{particle} = 1.00$ was chosen. The sample was then stabilized until equilibrium state was reached. At the end of this step, the internal stress state at center of the sample was calculated. The ratio between horizontal and vertical stresses was found equal to 0.5, which is close to classical "at rest" earth pressure ratio K_0. This ratio was also calculated from the stresses measured on sample boundaries. Finally, the sample was confined vertically on its top surface.

Table 1
A summary table with all DEM parameters used in penetration tests.

Parameter	Symbol	Value	Unit
Width box	L	0.6	m
Height box	H	0.45	m
Particle number	N_P	10 000	–
Average particle diameter	D_p	5.4	m
Particle density	ρ	2 700	kg m^{-3}
Normal contact stiffness	k_n	1.25×10^8	N/m
Tangential contact stiffness	k_s	9.375×10^7	N/m
Particle friction coefficient	$\mu_{particle}$	1.00	–
Rod friction coefficient	μ_{rod}	0.00	–
Tip friction coefficient	μ_{tip}	0.30	–

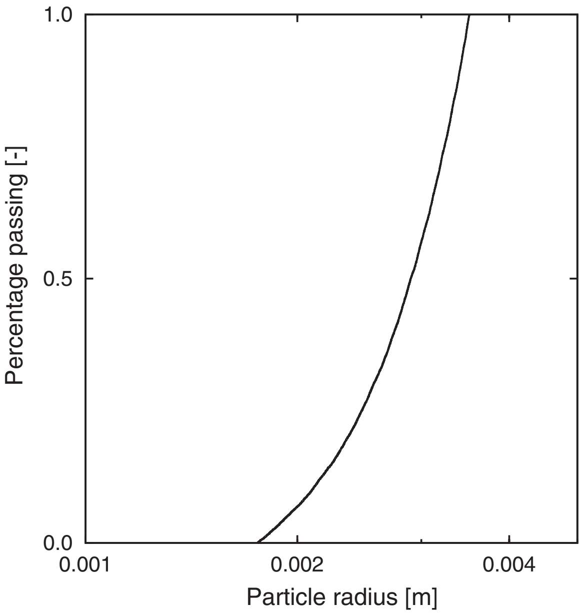

Fig. 3. Particle size distribution of the granular material.

Usually in homogeneous soils, tip resistance first increases with depth until a critical depth is reached and then tip resistance becomes steady (Fig. 1). The confining stress, equal to 40 kPa simulates an overlaying layer of material; it prevented the effects of free surface to be observed [14]. A linear contact model was used and the contact stiffness was chosen in order to assess the assumption of rigid particles during penetration tests [16,17]. A Coulomb friction criterion of coefficient $\mu_{particle} = 1.00$ was used to limit the value of tangential force relatively to normal force. No viscous damping was considered in the contact model and no local damping was used in the model [18]. Thus, energy is only dissipated by friction during the penetration tests.

Penetration tests were conducted on three different samples generated with the same conditions of density and particle grading but different initial particle arrangement. The penetration was performed with a frictionless rod of width 14 mm linked to a tip of 16 mm width at its bottom edge and presenting a friction coefficient μ_{tip} of 0.3 [2–4] (Fig. 4). In constant velocity conditions, called hereafter constant velocity conditions test, the rod is driven in the sample with a constant rod velocity up to 0.30 m of depth. The vertical component of the force applied by the granular material on the tip is called tip force F_c for penetration test conducted in constant velocity condition.

For tests conducted in impact conditions, the rod is first driven with constant velocity until a depth of 0.15 m is reached. The rod is then released and stabilized under its own weight. Then, series of five successive impacts are produced in each sample with an additional cylinder on the top of the rod (Fig. 4). The mass of the impacting cylinder is equal to the rod mass. The vertical component of the force applied by the granular material on the tip is called tip force F_d in impact condition tests. Equilibrium state is reached after each blow and before applying the next blow.

The equilibrium state used in the simulations is a classical equilibrium state condition. Once one of the two ratio values defined

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