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# Discrete modeling of penetration tests in constant velocity and impact conditions

Quoc Anh Tran, Bastien Chevalier and Pierre Breul

Correspondence to [bastien.chevalier@univ-bpclermont.fr](mailto:bastien.chevalier@univ-bpclermont.fr)

Clermont Université, Université Blaise Pascal, Institut Pascal, BP 10448, F-63000 Clermont-Ferrand, France.

CNRS, UMR 6602, Institut Pascal, F-63171 Aubière, France.

Tel. +33(0)4.73.40.75.23

Fax. +33(0)4.73.40.74.94

## 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  $25 \text{ mm}\cdot\text{s}^{-1}$  to  $5000 \text{ mm}\cdot\text{s}^{-1}$ . 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.

**Keywords:** DEM, Penetration test, Tip force, Penetration rate

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## 31 1. Introduction

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

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

40 Penetration tests generate large deformations and a highly non-homogeneous solicitation,  
 41 Discrete Element Method (DEM) is then a particularly relevant numerical method to model  
 42 this test. Many authors proposed numerical models for reproducing penetration tests in static  
 43 conditions i.e. in constant velocity conditions in 2D [5,6,7,8,9,10] and in 3D [1,4,11,12].  
 44 However, [1,13,14] showed that tip resistance depends on the loading type used in the  
 45 penetration process. Very few researches focus to the modeling of penetration tests in impact  
 46 conditions.

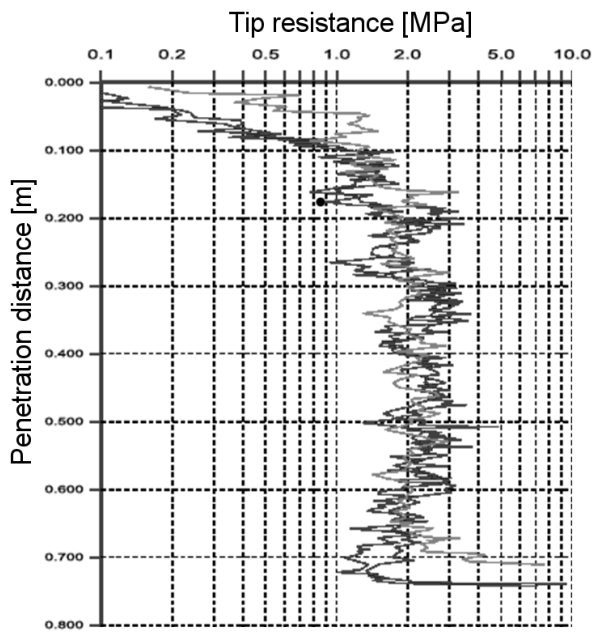


Figure 1. Example of an experimental result of a impact penetration test.

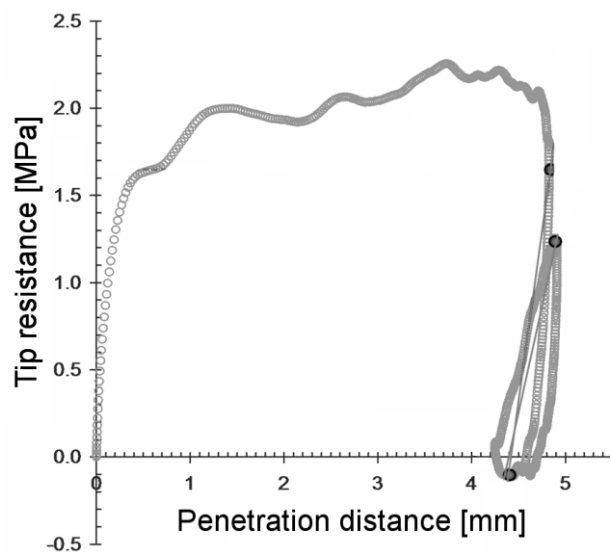
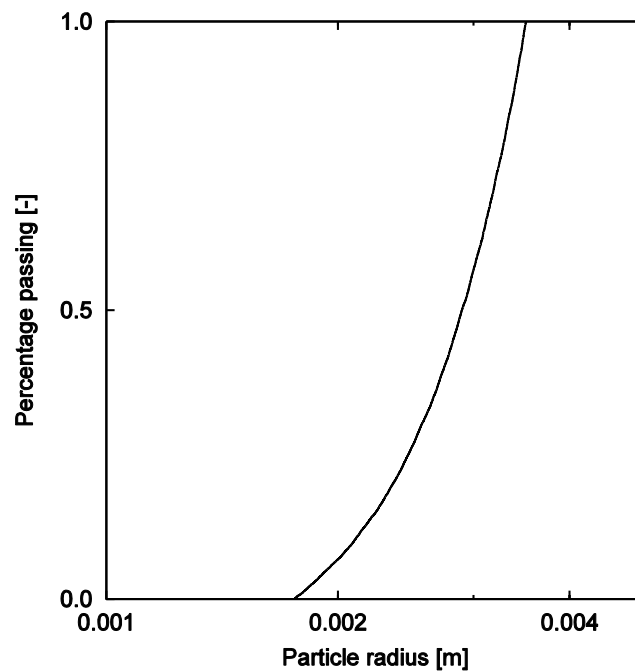


Figure 2. Example of experimental load–penetration curve obtained in a impact penetration test for one impact [2].

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

## 54 2. Numerical Model

55 Discrete Element Method in two dimensions was used with Itasca's software PFC<sup>2D</sup> [15].  
56 Table 1 summarize the parameter of the model. Granular material samples of 10 000  
57 cylindrical particles were generated and tested in a rectangular box (Table 1). A diameter ratio  
58 of 2 was chosen between largest and smallest particles. The average particle diameter of the  
59 material  $D_p$  is equal to 5.4 mm (Fig.3).



60  
61

Figure 3. Particle size distribution of the granular material.

62 The sample preparation broke down into 3 steps. First, a frictionless particle radius expansion  
63 method without gravity was used in order to reach a minimum value of sample porosity of  
64  $n = 0.15$ . Secondly, the final value of friction coefficient of  $\mu_{particle} = 1.00$  was applied as well  
65 as the gravity. We conducted simulations with different values of particle friction and found  
66 no influence of particle friction on the results for values of  $\mu_{particle} \geq 0.50$ . So the value of  
67  $\mu_{particle} = 1.00$  was chosen. The sample was then stabilized until equilibrium state was reached.

68 At the end of this step, the internal stress state at center of the sample was calculated. The  
 69 ratio between horizontal and vertical stresses was found equal to 0.5, which is close to  
 70 classical “at rest” earth pressure ratio  $K_0$ . This ratio was also calculated from the stresses  
 71 measured on sample boundaries. Finally, the sample was confined vertically on its top  
 72 surface.

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

<i>Parameter</i>	<i>Symbol</i>	<i>Value</i>	<i>Unit</i>
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	$\rho$	2 700	kg.m <sup>-3</sup>
Normal contact stiffness	$k_n$	1.25 x 10 <sup>8</sup>	N/m
Tangential contact stiffness	$k_s$	9.375 x 10 <sup>7</sup>	N/m
Particle friction coefficient	$\mu_{particle}$	1.00	-
Rod friction coefficient	$\mu_{rod}$	0.00	-
Tip friction coefficient	$\mu_{tip}$	0.30	-

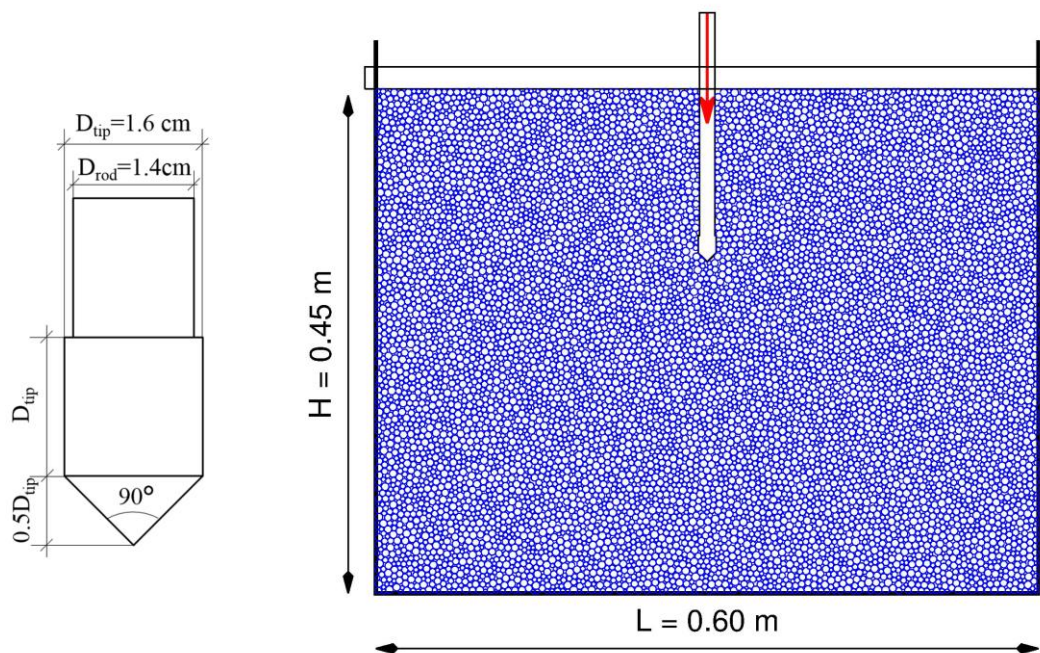
82 Table 1. A summary table with all DEM parameters used in penetration tests.

83 Penetration tests were conducted on three different samples generated with the same  
 84 conditions of density and particle grading but different initial particle arrangement. The  
 85 penetration was performed with a frictionless rod of width 14 mm linked to a tip of 16 mm  
 86 width at its bottom edge and presenting a friction coefficient  $\mu_{tip}$  of 0.3 [2,3,4] (Fig.4). In  
 87 constant velocity conditions, called hereafter constant velocity conditions test, the rod is  
 88 driven in the sample with a constant rod velocity up to 0.30 m of depth. The vertical

89 component of the force applied by the granular material on the tip is called tip force  $F_c$  for  
90 penetration test conducted in constant velocity condition.

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

98 The equilibrium state used in the simulations is a classical equilibrium state condition. Once  
99 one of the two ratio values defined hereafter decreases below a given value, the system is  
100 considered in mechanical equilibrium. The first ratio is given by the ratio of average  
101 unbalanced force magnitude of particles to average magnitude of normal contact force. The  
102 second ratio is given by the ratio of the magnitude of the greatest unbalanced force on  
103 particles to the magnitude of the greatest normal contact force.



104  
105

Figure 4. Tip details and sample of granular material tested.

106 Figure 5 shows the tip force  $F_c$  versus the depth in a given sample of 0.60 m width for depth  
107 between 0.15 m and 0.30 m, obtained with a rod velocity of  $25 \text{ mm.s}^{-1}$ . Despite some  
108 oscillations, due to coarse nature of the material, it is found that  $F_c$  is relatively steady in

109 average as the depth increases and is keeping with an experimental constant velocity  
110 penetration test. The upper confining stress cancelled the effect of the free surface.

111 In order to highlight the effect of sample width on the test results, constant velocity  
112 penetration tests were conducted in boxes of different width ranging from 0.15 m to 0.90 m.  
113 The penetration rate used is equal to  $1250 \text{ mm}\cdot\text{s}^{-1}$ , which represents an average value of  
114 penetration rates used in this study (constant velocity and impact conditions). Figure 6 shows  
115 the probability distribution of  $F_c$  obtained for samples width varying between 0.15 m and  
116 0.90 m. As the box width increases, we observe that the probability distribution of the values  
117 of  $F_c$  becomes stable when the width is greater than 0.60 m.

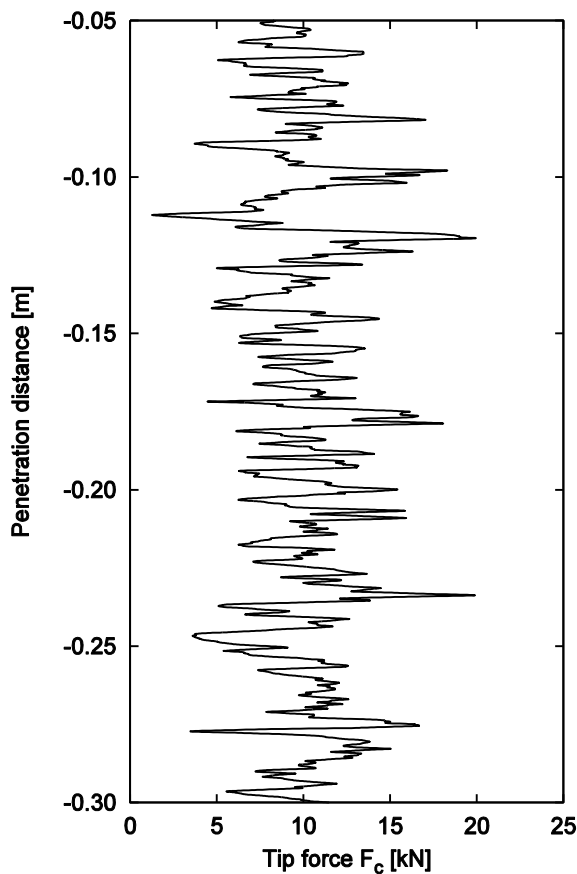


Figure 5. Tip force  $F_c$  versus penetration distance obtained at  $25 \text{ mm}\cdot\text{s}^{-1}$  of rod velocity in the sample of 0.6 m width.

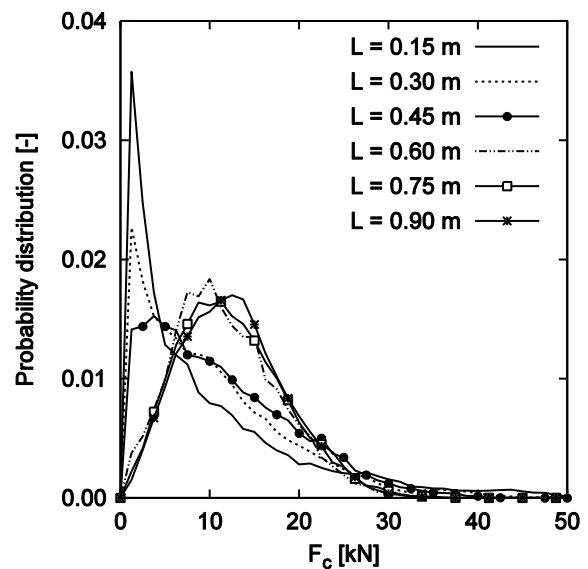


Figure 6. Probability distribution of tip force  $F_c$  between 0.05 and 0.30 m of penetration distance at  $1250 \text{ mm}\cdot\text{s}^{-1}$  of rod velocity for different samples width  $L$ .

118 3. Effect of penetration rate on the tip force in constant  
 119 velocity penetration test

120 In this section, we focus on the influence of the driving velocity on the tip force  $F_c$  for  
 121 constant velocity penetration tests. The penetration rates range from a low value of,  $25 \text{ mm.s}^{-1}$   
 122 corresponding to penetration rate prescribed in the standards for constant velocity penetration  
 123 test to a fast penetration rate corresponding to the order of magnitude of impact velocity used  
 124 in impact conditions  $5000 \text{ mm.s}^{-1}$  as described in [1,2].

125 Figure 7 shows the probability distributions of all values of tip force  $F_c$  measured between  
 126 0.05 m and 0.30 m of penetration depth obtained for three samples with different penetration  
 127 rates [19]. Probability distributions of tip force  $F_c$  complies with the normal law when  
 128 penetration rate is lower than  $1250 \text{ mm.s}^{-1}$ . The dispersion of  $F_c$  increases when rod velocity  
 129 is higher than  $1250 \text{ mm.s}^{-1}$ .

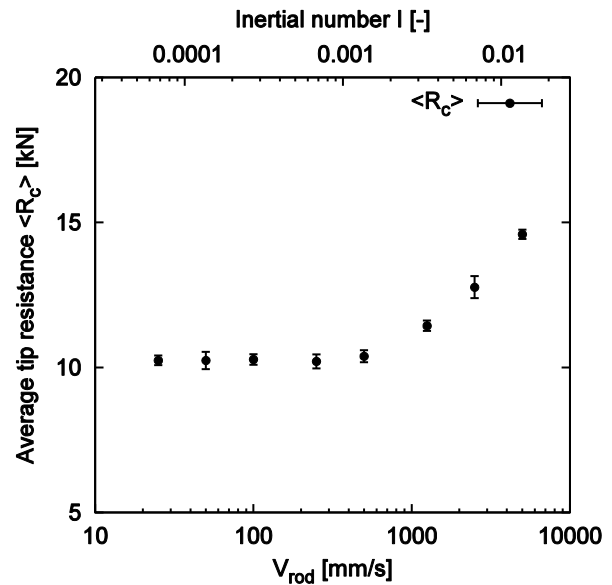
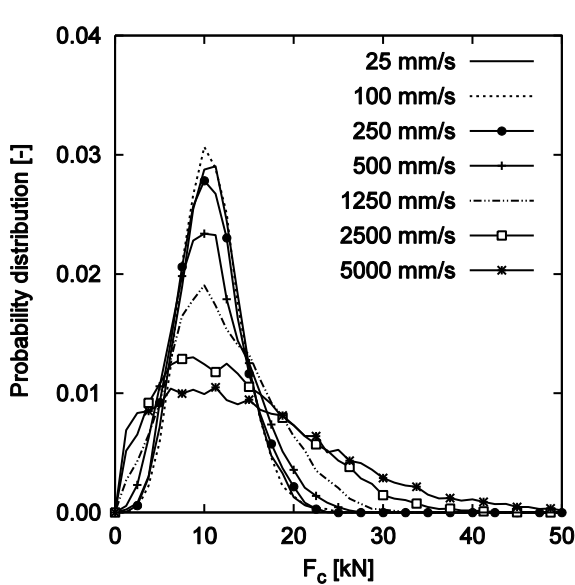


Figure 7. Probability distribution of tip force  $F_c$  between 0.05 and 0.30 m of penetration distance for three samples with different rod velocities [19].

Figure 8. Average tip resistance  $\langle R_c \rangle$  versus rod velocity (height of vertical bars represent twice the standard deviation of  $R_c$ ).

130 The non-dimensional inertial number  $I$  can be used to quantify dynamic effects in both  
 131 experimental tests and numerical modeling [17]. Inertial number is given by

$$I = \dot{\gamma} \sqrt{\frac{m}{P}} \quad (1)$$

132 with  $\dot{\gamma}$  the shearing rate of the particle assembly during penetration testing,  $m$  the average  
 133 particle mass and  $P$  the confinement stress. It can be used to differentiate the regimes of



134 solicitation: from quasi-static state with  $I < 10^{-3}$  to inertial state with  $I > 10^{-3}$  [17]. It is  
135 difficult to determine the shearing rate for penetration tests since the deformation applied to  
136 the material is highly non-homogeneous. In order to get an order of magnitude of the inertial  
137 number, the deformation rate is calculated by the formula being proposed based on  $V_{rod}$  the  
138 rod velocity;  $H$  the sample height:

$$\dot{\gamma} = \frac{V_{rod}}{H} \quad (2)$$

139 The inertial number  $I$  defined by Eq.1 & 2 increases from  $6.80 \times 10^{-5}$  to  $1.36 \times 10^{-2}$  according to  
140 the penetration rate (from  $25 \text{ mm.s}^{-1}$  up to  $5000 \text{ mm.s}^{-1}$ ).

141 The tip resistance  $R_c$  is defined here as the average of  $F_c$  obtained between 0.05 and 0.30 m of  
142 penetration distance in a given sample. The average tip resistance  $\langle R_c \rangle$  obtained on three  
143 different samples is calculated.

144 It can be observed on Fig.8 that  $\langle R_c \rangle$  remains constant when the rod velocity is lower than  
145  $1250 \text{ mm.s}^{-1}$ . Then,  $\langle R_c \rangle$  increases rapidly for penetration rate upper than  
146  $1250 \text{ mm.s}^{-1}$  corresponding to an inertial number  $I$  (in the order of  $3.40 \times 10^{-3}$ ). It can also be  
147 noticed on Fig.7 that the dispersion of tip force  $F_c$  also increases with rod velocity.

148 The same trend was described in [4]. In this paper, tip resistance  $q_c$  is steady for low value of  
149 penetration rates and then increases as penetration rate increases. In both studies, the change  
150 of regime occurs for different values of the rod velocity, because this value probably depends  
151 on particle size distribution, tip size, confining stress  $P$  (as show in Eq.1&2) and possibly  
152 additional parameters.

#### 153 4. Effect of penetration rate on the tip force in impact 154 penetration test

155 For impact penetration tests, impacts are generated on the top of the driving rod and the tip  
156 force  $F_d$  is measured as well as the penetration distance.

157 The effect of impact energy is significant in impact penetration tests. The impact test were  
158 compared in terms of maximal rod velocity and not in terms of impact velocity. In order to  
159 show that rod maximal velocity is dependent on impact energy, impact tests were conducted  
160 with same impact energy but with changing impact mass and impact velocities The ratio  
161 between impact mass and rod mass ( $\xi$ ) for successively taken equal to 0.5, 1.0 and 2.0. Figure

162 9 presents the three curves of versus penetration distance obtained. First, the magnitude of  $F_d$   
 163 is similar for 3 cases. Furthermore, the same maximum rod velocity  $V_{rodmax} \cong 1210 \text{ mm.s}^{-1}$  is  
 164 obtained in the different cases corresponding to different ratios  $\xi$  (Fig.10).

165 Secondly, the response obtained with the model is similar to the one classically obtained  
 166 experimentally (Figure 2), it breaks down into three phases (Fig.9,10):

- 167 • a quick loading phase corresponding to the initial increase of the rod velocity. In this  
 168 phase, whatever is the blow, the signal shape is similar. The duration of this phase is  
 169 the same as the duration of the impact ( $t_{impact} \approx 2.2 \text{ ms}$ ). The first point (1)  
 170 corresponds to the time when the rod velocity reaches its maximum velocity.
- 171 • a plastic phase corresponding to the penetration process of the rod in the soil. In this  
 172 phase, the signal shows oscillations depending on the arrangement of the granular  
 173 material. The second point (2) corresponds to a moment in this phase when the rod  
 174 velocity decreases. The point (3) corresponds to the moment when the penetration  
 175 distance is maximal: the rod velocity is equal to zero.
- 176 • a phase of unloading–loading cycles corresponding to the stabilization of the rod. The  
 177 fourth point (4) shows the moment when the rod velocity is zero for second time.

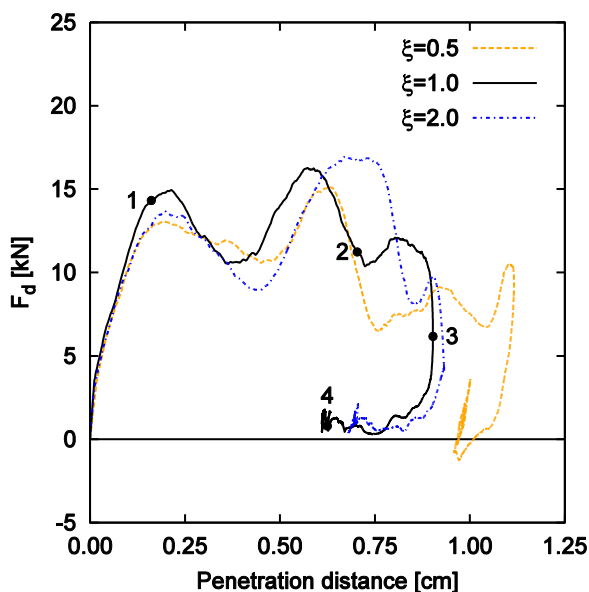


Figure 9. Examples of load–penetration curves obtained for 3 tests performed with the same impact energy.

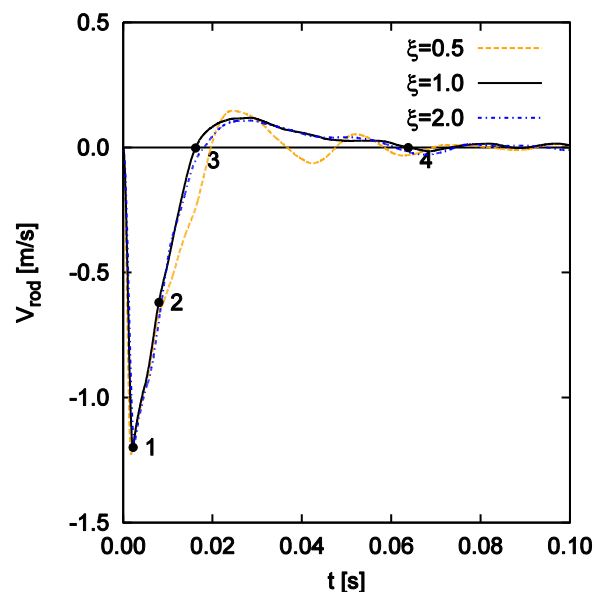
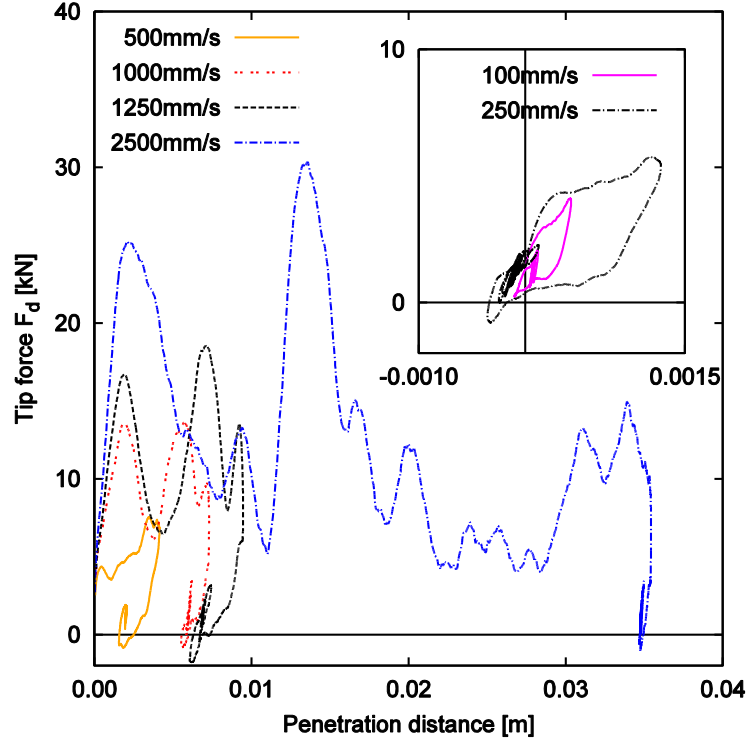


Figure 10. Rod velocity versus time during a impact penetration test for for 3 tests performed with the same impact energy.

178 Figure 11 shows the load–penetration curve for different impact velocities ( $\xi = 1.0$ ). For an  
 179 impact velocity of 250 mm/s or smaller, the energy injected is not large enough to drive the  
 180 rod in the medium: at the end of the impact test, the tip comes back to its initial position; the  
 181 tip force first increases and then rapidly decreases; the plastic phase of load–penetration curve

182 (Fig.9) is not observed. For impact velocity of  $500 \text{ mm}\cdot\text{s}^{-1}$  or greater, the tip does not come  
 183 back completely to its initial position. Figure 11 shows that the minimal velocity required to  
 184 penetrate the granular material is a value between  $250$  and  $500 \text{ mm}\cdot\text{s}^{-1}$ . When the impact  
 185 velocity is greater than  $500 \text{ mm}\cdot\text{s}^{-1}$ , the plateau of the load–penetration curve corresponding to  
 186 the plastic phase is observed.



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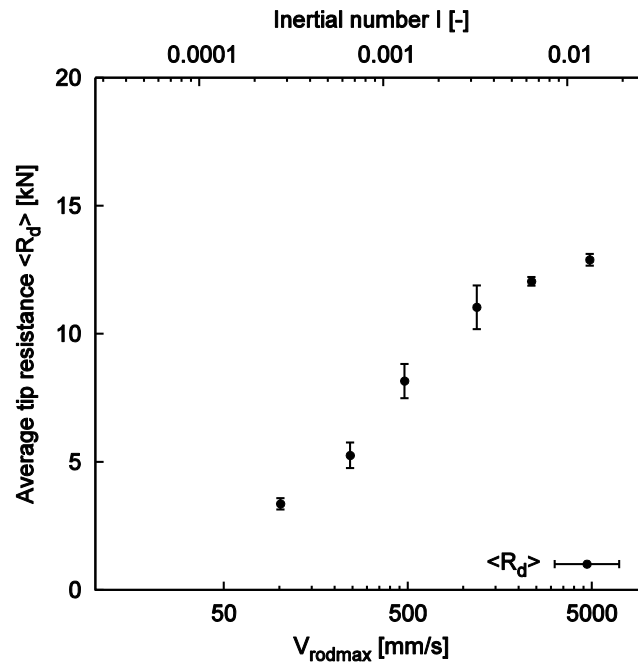
188 Figure 11. Load versus penetration distance for different impact velocities for impact penetration test.

189 Although, there is a difference between the maximal penetration distance  $s_{max}$  and the final  
 190 residual penetration distance  $s_{res}$  due to the rebound of the rod at the end of the test, the work  
 191 of the tip force between these two positions is negligible. Consequently, the impact tip  
 192 resistance  $R_d$  of each sample was calculated as the average tip force  $F_d$  for penetration  
 193 distance between 0 and maximal value  $s_{max}$ :

$$R_d = \frac{1}{5} \sum_{i=1}^5 \left\{ \frac{1}{s_{max}} \int_{t=0}^{t_{s_{max}}} F_d(t) ds(t) \right\}_i \quad (3)$$

194 with  $t$  the time and  $t_{s_{max}}$  the time when penetration distance is maximal and equal to  $s_{max}$ .

195  $\langle R_d \rangle$  is the average value of impact tip resistances obtained on 3 samples. Figure 12 shows  
 196 the curve of  $\langle R_d \rangle$  versus maximal rod velocity  $V_{rodmax}$  for different impact energy. We find  
 197 that  $\langle R_d \rangle$  increases when the rod velocity increases.

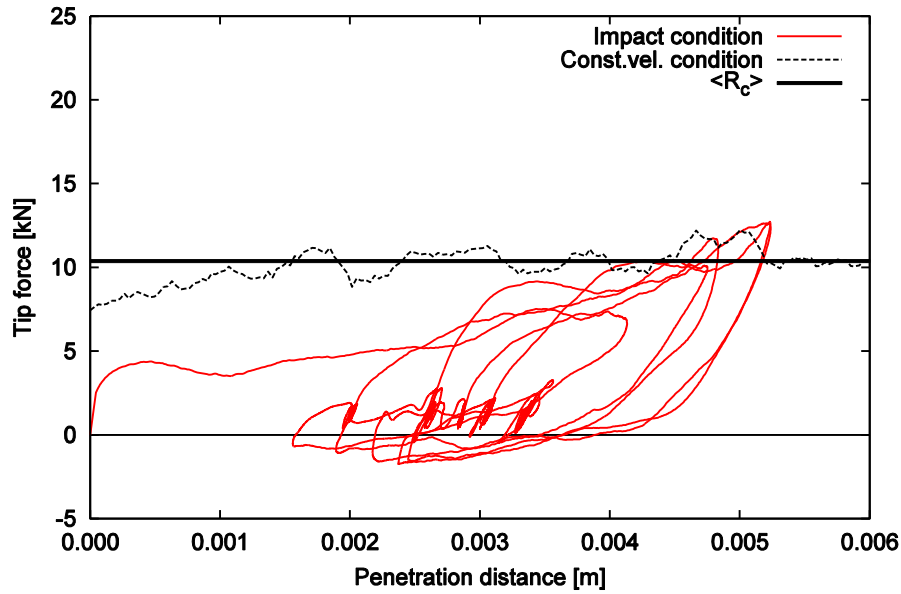


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199 Figure 12. Average tip resistance  $\langle R_d \rangle$  versus maximum rod velocities. Upper x-axis shows the corresponding  
 200 values of inertial number (height of vertical bars represent twice the standard deviation of  $R_d$ ).

## 201 5. Tip force comparison for constant velocity and impact 202 conditions with different rod velocities

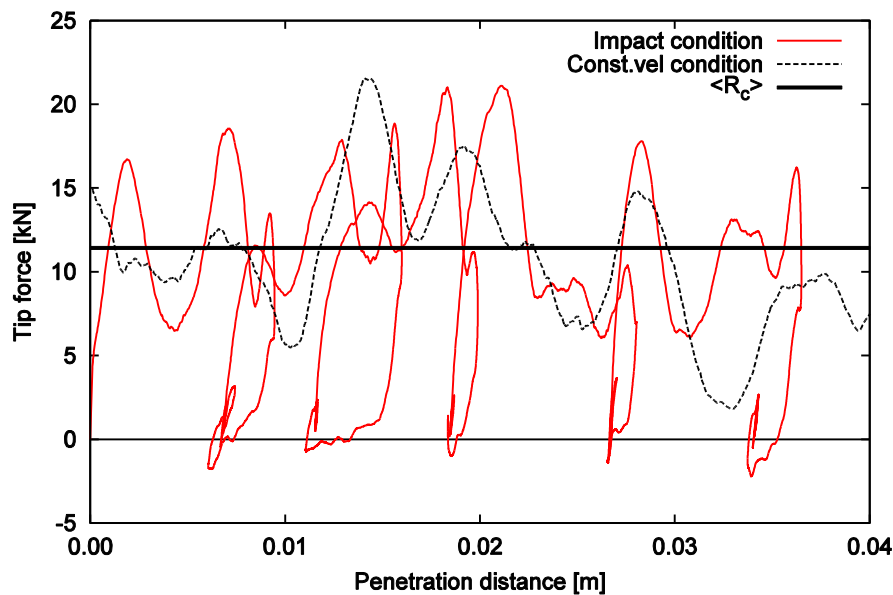
203 Figure 13 presents the tip force versus penetration distance in both constant velocity and  
 204 impact conditions for a rod velocity of  $500 \text{ mm}\cdot\text{s}^{-1}$ , corresponding to the quasi-static regime  
 205 of solicitation. We found that the amplitude of tip force  $F_d$  is weaker than the average tip  
 206 force  $\langle R_c \rangle$ . This observation is correlated to the fact that in impact conditions, the impact  
 207 energy is not sufficient for driving the rod through the granular material. At the end of the  
 208 phase 1,  $F_d$  reaches the value of  $F_c$  but then  $F_d$  immediately decreases.



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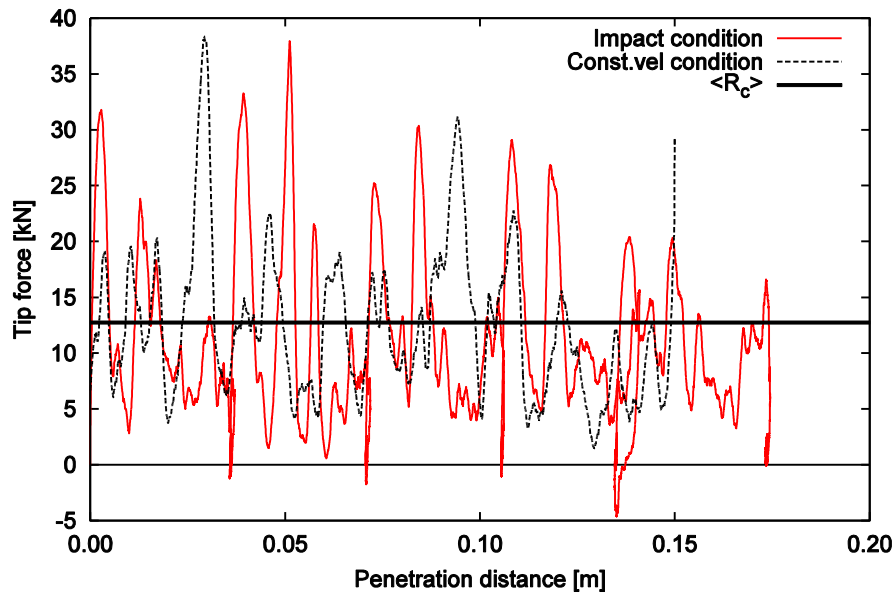
210 Figure 13. Tip force versus penetration distance for constant velocity penetration test with  $V_{rod} = 500 \text{ mm.s}^{-1}$  and  
 211 for 5 blows of impact penetration tests performed with  $V_I = 500 \text{ mm.s}^{-1}$ .

212 Figures 14 and 15 present the tip force versus penetration distance in both constant velocity  
 213 and impact conditions at  $1250 \text{ mm.s}^{-1}$  and  $2500 \text{ mm.s}^{-1}$  of rod velocity range. For this  
 214 penetration rate, the particle behavior is in the dense flow regime. In contrast to  $500 \text{ mm.s}^{-1}$  of  
 215 rod velocity range, we get to generate sufficient energy from the impact to activate the plastic  
 216 phase. We found that the tip force amplitude is similar in both constant velocity and impact  
 217 conditions. In addition, the tip force oscillations become more important when the penetration  
 218 rate increases (Fig.14,15).



219

220 Figure 14. Tip force versus penetration distance for constant velocity penetration test with  $V_{rod} = 1250 \text{ mm.s}^{-1}$   
 221 and for 5 blows of impact penetration tests performed with  $V_I = 1250 \text{ mm.s}^{-1}$ .



222

223 Figure 15. Tip force versus penetration distance for constant velocity penetration test with  $V_{rod} = 2500 \text{ mm.s}^{-1}$   
 224 and for 5 blows of impact penetration tests performed with  $V_I = 2500 \text{ mm.s}^{-1}$ .

225 Figure 16 presents the comparison between the average tip forces obtained in constant  
 226 velocity and impact conditions at different penetration rates. In fact, the average tip force in a  
 227 homogeneous medium is stable in the zone where the surface effect is prevented by the  
 228 vertical confining stress used on top wall. Thus, the average tip force do no depend on the  
 229 penetration distance for any penetration condition. We note that  $\langle R_d \rangle$  is presented in impact  
 230 condition as function of maximal rod velocity  $V_{rodmax}$ . In quasi-static regime and for similar  
 231 rod velocity, we found that the  $\langle R_d \rangle$  is smaller than the one obtained in constant velocity  
 232 penetration test. In dense flow regime ( $V_{rod} \geq 1250 \text{ mm.s}^{-1}$ ),  $\langle R_d \rangle$  becomes close to  $\langle R_c \rangle$ . For  
 233 high impact energy, the rod velocity in impact condition increases only during the impact.  
 234 After that, the rod velocity decreases due to the reaction of the particles below the tip. Thus,  
 235 the  $\langle R_c \rangle$  can be always greater than  $\langle R_d \rangle$  for all rod velocities in dense flow regime.

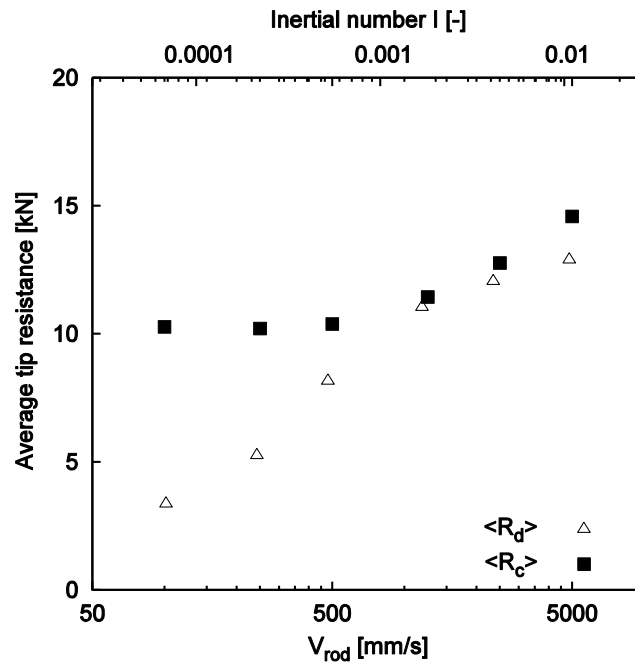


Figure 16. Average tip resistances  $\langle R_c \rangle$  and  $\langle R_d \rangle$  versus rod velocity.

236

237

238 In 3D conditions, we can assume that, as in 2D, an impact energy which is too low can be  
 239 insufficient to penetrate the material and then to measure a representative tip resistance. On  
 240 the opposite, for penetration rates high enough, a tip resistance can be measured in impact  
 241 condition. The increase of tip resistance with the rod velocity was observed in 3D conditions  
 242 in [4]. In addition, in experimental tests, it is commonly observed that static penetration  
 243 resistance, measured with low penetration velocity, is lower than dynamic tip resistance,  
 244 which is measured with relatively high penetration rates. The same trend is observed here on  
 245 Fig.16: tip resistance in impact condition, for higher rod velocity is greater than tip resistance  
 246 in constant velocity condition obtained with lower velocity.

## 247 6. Conclusion

248 A 2-dimensional discrete numerical model was proposed to model penetration tests in  
 249 granular materials. Two types of tests were performed: constant velocity conditions tests and  
 250 impact conditions tests. The responses obtained in terms of tip forces versus penetration depth  
 251 is similar to classical experimental results.

252 Penetration test in soils actually is a three-dimensional problem but was simulated here in  
 253 plane strain or two dimensions in this study. It is true that an assembly of disks cannot capture  
 254 exactly the behavior of a real granular material. However, the study presented here focuses  
 255 only on the mechanisms involved in two different types of penetration tests and on the effect  
 256 of driving velocity. The study presented here has no intention to link directly and

257 quantitatively the results obtained in 2D with 3D modelling or field penetration tests. Yet, the  
258 basic laws governing the behavior of a mechanical system such as assemblies of disks or  
259 spheres are supposed to be shared between those different kinds of systems. Indeed, number  
260 of studies proved 2D DEM to be efficient in describing soil behavior [10]. Also, the basic  
261 trends observed here are in agreement with other papers focused on 3D simulations.

262 The effect of penetration rate on constant velocity and impact penetration tests where  
263 investigated. The particle behavior changes from quasi-static regime to dense flow regime  
264 when rod velocity range varies from  $25 \text{ mm.s}^{-1}$  to  $5000 \text{ mm.s}^{-1}$  with a transition value around  
265  $1250 \text{ mm.s}^{-1}$ .

266 In constant velocity condition, the tip force is stable when the rod velocity is lower than  
267  $1250 \text{ mm.s}^{-1}$ . However, the average tip resistance and the dispersion of tip force increase  
268 rapidly when the particle behavior in dense flow regime for a tip velocity greater than  
269  $1250 \text{ mm.s}^{-1}$ .

270 In impact condition, the load-penetration curves consists in 3 different phrases. The variation  
271 of tip force increases in terms of amplitude when the impact velocity increases. In addition,  
272 the energy injected is not large enough to drive the rod in the medium in impact condition  
273 when the impact velocity is lower than  $500 \text{ mm.s}^{-1}$ .

274 Finally, the tip forces obtained from impact and constant velocity penetration tests were  
275 compared. In quasi-static regime corresponding to impact velocities less than  $500 \text{ mm.s}^{-1}$ , the  
276 impact energy is not sufficient for driving the rod through the granular material. For greater  
277 impact energy, the amplitude of tip force is closer to but lower than average tip resistance  
278  $\langle R_c \rangle$  obtained in constant velocity test with the same rod velocity. When comparing constant  
279 velocity and impact tests, the rod velocity in impact test is the same as in the constant velocity  
280 test only at the beginning of the penetration process; as the tip penetrates the material, its  
281 velocity progressively decreases and the resulting tip force is lower.

282 In future tests, it would be interesting to quantify the influence on the results of the contact  
283 model and also consider the effect of particle crushing in order to refine the analysis of the  
284 results.

## 285 Reference

286 [1] Benz Navarrete, M. (2009). *Mesures dynamiques lors du battage du pénétromètre*  
287 *Panda 2*. PhD thesis, Clermont-Ferrand: Université Blaise Pascal.



- 288 [2] Benz, M.A., Escobar, E., Gourvès, R., Haddani, Y., Breul, P. & Bacconnet, C. (2013).  
289 Dynamic measurements of the penetration test - Determination of the tip's dynamic load-  
290 penetration curve. *Proc. of the 18th Int. Conf. on the Soil Mech. and Geotech. Eng., Paris*,  
291 499 – 502.
- 292 [3] Breul, P., Benz, M., Gourvès, R., & Saussine, G. (2009, June). Penetration Test  
293 Modelling in a Coarse Granular Medium. In *Powders and Grains 2009: Proceedings of the*  
294 *6th International Conference on Micromechanics of Granular Media* (Vol. 1145, No. 1, pp.  
295 173 - 176). AIP Publishing.
- 296 [4] Quezada, J. C., Breul, P., Saussine, G., & Radjai, F. (2014). Penetration test in coarse  
297 granular material using Contact Dynamics Method. *Computers and Geotechnics*, 55, 248–  
298 253.
- 299 [5] Huang, A. B. & Ma, M. Y. (1994). An analytical study of cone penetration test in  
300 granular material. *Canadian Geotechnical Journal* 31, No.1, 91 – 103.
- 301 [6] Huang, A. B. & Hsu, H. H. (2004). Advanced calibration chambers for cone  
302 penetration testing in cohesionless soils. *ISC-2 Geotech. and Geophys. Site Characterization*,  
303 *Porto*, 147 – 166.
- 304 [7] Calvetti, F. & Nova, R. (2005). Micro-macro relationships from DEM simulated  
305 element and in-situ tests. *Proc. 5th Int. Conf. Micromech. Granular Media: Powders and*  
306 *Grains 2005, Stuttgart*, 245 – 250.
- 307 [8] Jiang, M. J., Yu, H.-S. & Harris, D. (2006). Discrete element modeling of deep  
308 penetration in granular soils. *International Journal for Numerical and Analytical Methods in*  
309 *Geomechanics* 30, No. 4, 335 – 361.
- 310 [9] Jiang, M. J., Harris, D., & Zhu, H. (2007). Future continuum models for granular  
311 materials in penetration analyses. *Granular Matter*, 9(1), 97–108.
- 312 [10] Jiang, M., Dai, Y., Cui, L., Shen, Z., & Wang, X. (2014). Investigating mechanism of  
313 inclined CPT in granular ground using DEM. *Granular Matter*, 16(5), 785-796.
- 314 [11] Arroyo, M., Butlanska, J., Gens, A., Calvetti, F. & Jamiolkowski, M. (2011). Cone  
315 penetration tests in a virtual calibration chamber. *Géotechnique* 61, No. 6, 525 – 531.

- 316 [12] McDowell, G. R., Falagush, O. & Yu, H. S. (2012). A particle refinement method for  
317 simulating DEM of cone penetration testing in granular materials. *Géotechnique Letters* 2,  
318 141 – 147.
- 319 [13] Robertson, P. K., & Campanella, R. G. (1983). Interpretation of cone penetration  
320 tests. Part I: Sand. *Canadian Geotechnical Journal*, 20(4), 718-733.
- 321 [14] Chaigneau, L. (2001). *Caractérisation des milieux granulaires de surface à l'aide d'un*  
322 *pénétromètre*. PhD thesis. Clermont-Ferrand: Université Blaise Pascal.
- 323 [15] Cundall P. A. & Strack O. D. L. (1979). A discrete numerical model for granular  
324 assemblies. *Géotechnique* 29, No. 1, 47 – 65.
- 325 [16] Combe G. (2002) Mécanique des matériaux granulaires et origines microscopiques de  
326 la déformation. *Etudes et Recherches du Laboratoire Central des Ponts et Chaussées*, SI8.
- 327 [17] Roux, J.-N., & Chevoir, F. (2005). Discrete numerical simulation and the mechanical  
328 behavior of granular materials. *Bulletin Des Laboratoires Des Ponts et Chaussées*, (254),  
329 109 – 138.
- 330 [18] Cundall P.A., Drescher A. & Strack O.D.L. (1982). Numerical experiments on  
331 granular assemblies: measurements and observations. *IUTAM Conf. on Deformation and*  
332 *Failure of Granular Materials, Delft*, 355 - 370.
- 333 [19] Tran, Q. A., Chevalier, B., & Breul, P. (2015). A numerical study of the penetration  
334 test at constant rod velocity. *Computer Methods and Recent Advances in Geomechanics –*  
335 *Oka, Murakami, Uzuoka & Kimoto (Eds.)*, p. 193-198.