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SIMULATION OF PENETRATION PROBLEMS IN GEOMECHANICS

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Abstract. The simulation of penetration problems in geomaterials is a challenging problem as it involves large deformations and displacements as well as strong non-linearities affecting material behaviour, geometry and contact surfaces. The paper presents examples of modelling of the cone penetration test using two procedures: a discrete approach and a continuum approach. The discrete approach is based on the Discrete Element Method where a granular material is represented by an assembly of separate particles. Cone penetration has been successfully simulated for the case of crushable sands. For the continuum approach, the Particle Finite Element Method has been adopted. The procedure has been effectively applied to the modeling of undrained cone penetration into clays. Although not exempt of problems, both approaches yield realistic results leading to the possibility of a closer examination and an enhanced understanding of the mechanisms underlying penetration problems in geomechanics.

1 INTRODUCTION

Penetration problems are encountered very frequently in geotechnical engineering and other geomechanical applications. Some examples are the use of tube samplers to recover soil specimens, the installation of driven piles in the ground or a variety of penetration probes for site investigation purposes. A realistic numerical simulation of those type of problems would yield important advantages concerning the understanding of the processes involved during penetration possibly leading to a more rational approach for, among others, in-situ test interpretation, assessment of sampling disturbance and pile design.

However, the numerical simulation of penetration problems faces significant challenges as it involves large deformations and displacements as well as strong non-linearities affecting material behaviour, geometry and contact surfaces. A variety of computational techniques are available to tackle this kind of problems [1]. They can be classified into two main categories: discrete and continuum.

In this paper, both types of numerical modelling are applied to the same penetration problem: the cone penetration test (CPT). The CPT is a widely used site investigation tool for geomechanical applications. The test consists of the introduction of a cone, of standard dimensions, into the ground at a constant rate of penetration. The unit cone resistance is measured in a quasi-continuous manner during penetration. Normally, lateral friction and pore pressures are also measured but here attention is mainly focused on cone resistance. In this contribution, two examples of application are presented: the Discrete Element Method (DEM) for cone penetration in crushable sands and the Particle Finite Element Method (PFEM) for the undrained analysis of cone penetration in clays.

2 DEM MODELLING OF CONE PENETRATION IN CRUSHABLE SANDS

In the DEM modelling, the granular soil is represented by a number of finite size particles that interact through their contacts. The method tracks the motion of those particles subjected to a series of forces transmitted by the adjacent particles through the contacts [2]. The method has certainly important limitations bus also a considerable number of advantages [3]. Among the limitations are the generally oversimplified geometrical representation of the particles (often assumed to be spheres) and the need to scale up their size, especially in boundary value problems such as the cone penetration analyses. The main advantage is that large strains, displacements and rotations are readily accommodated in the analyses. Also, it is possible to bypass the need for quite sophisticated constitutive models for sands; instead, only the contact law between pairs of individual particles is usually required. It should be noted, however, that there is considerable uncertainty over the precise form of those contact laws and their parameters are generally calibrated comparing the macroscopic response of a DEM model and the results of analogous laboratory tests.

The modeling of cone penetration in materials made up of weak grains (e.g. calcareous sands) is especially interesting because it has been observed [4] that the pattern of cone resistance increase with relative density is notably different in calcareous crushable sand compared to non-crushable silica sand. This difference results in difficulties when correlations developed for silica sands are applied to materials with crushable grains [5-6]. In this context, the application of DEM analysis is appealing because it allows the isolation of the effects of grain strength and crushability. It is applied to an extreme case, reported in [7], where the cone resistance observed in calibration chamber tests was insensitive to relative density (Figure 1). The material is volcanic pumice sand the grains of which are porous themselves.

To model such materials, it is necessary to introduce particle crushing into the DEM formulation. Here, an efficient formulation recently developed has been adopted [8-9]. The main features of this approach can be summarized as follows: a particle failure criterion inspired by the analytical work of [10-11], a particle spawning procedure based on Apollonian packing and upscaling rules for particle strength and contact stiffness parameters. As in many multigenerational approaches, mass is not conserved after particle splitting but the missing mass of broken particles is allocated, during post-processing, to finer fractions according to a fractal distribution. In this way, it is possible to track evolving porosity and grain size distribution.

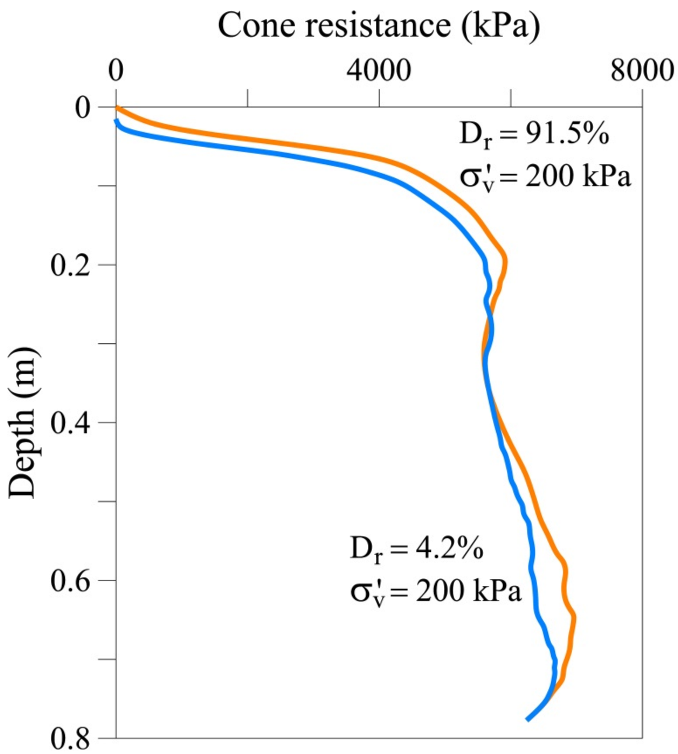

Figure 1: CPT results observed in cone penetration tests on pumice sand performed in a calibration chamber [7]

The corresponding virtual calibration chamber (Figure 2) has been constructed with the same procedure and scaling reported in [12]. The zero-strain radial lateral condition of the physical chamber was replicated by the model. The DEM model has been calibrated against oedometer and triaxial tests on the pumice sand used in the calibration chamber tests [7]. Selected results of the DEM analyses are presented in Figure 3 where it is apparent that the cone penetration values are quite insensitive to the density of the sand, as observed in the physical experiments.

Parallel DEM calculations assuming uncrushable grains were also performed so that the effects of particle crushability could be readily identified. Results in terms of ratio of cone penetration resistance of uncrushable and crushable granular materials are collected in Figure 4. It can be noted that the pattern of variation with relative density agrees well with reported experimental results. No DEM results are available for densities below about 40% due to the difficulty of constructing very loose virtual specimens. In any case, it appears that the use of the new DEM formulation for crushable materials provides a good tool to further explore penetration problems in this type of materials. More information on this study is given in [13].

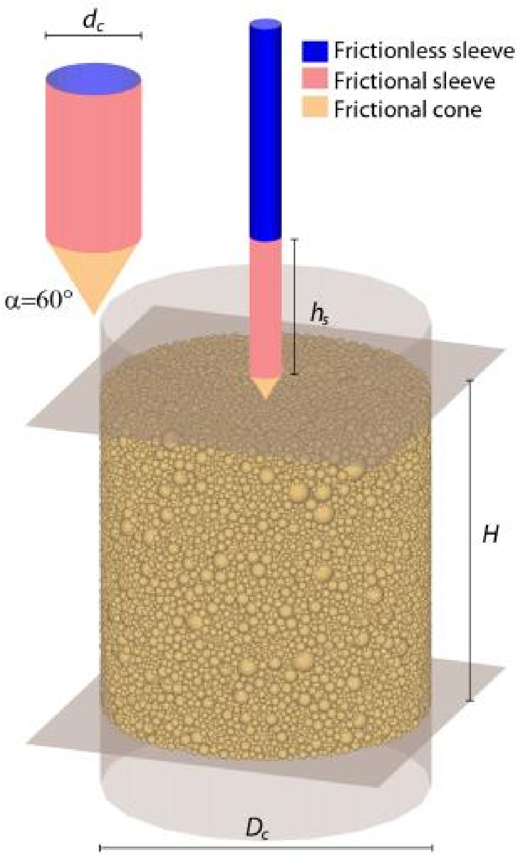

Figure 2: Scheme of DEM analysis: virtual calibration chamber and cone

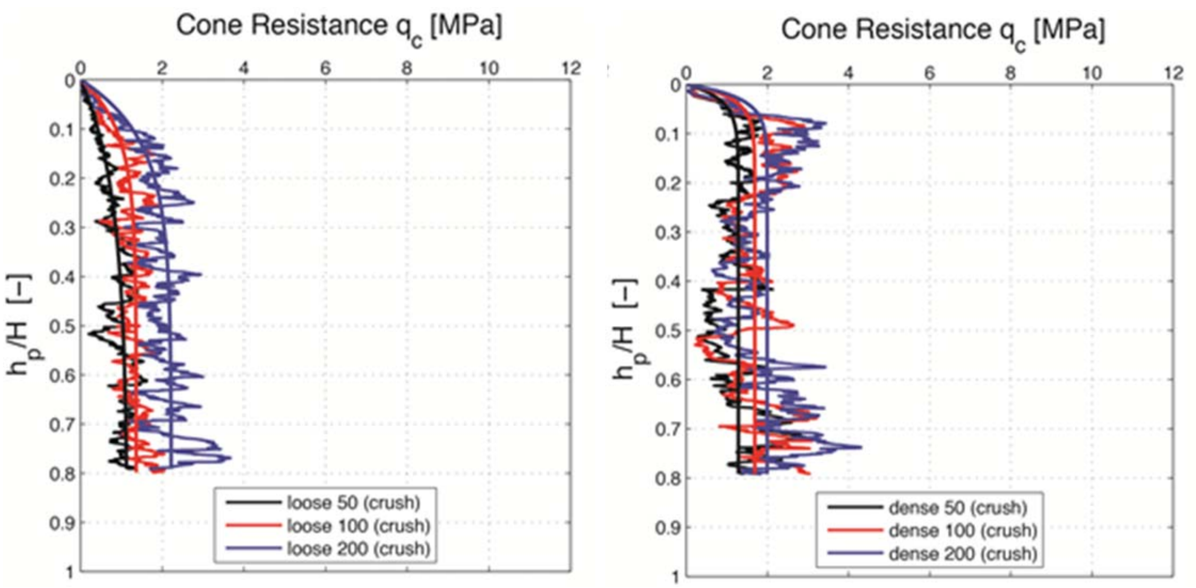

Figure 3: Computed cone resistance in simulated cone penetration on pumice sand at different stress values a) Loose specimen, b) Dense specimen

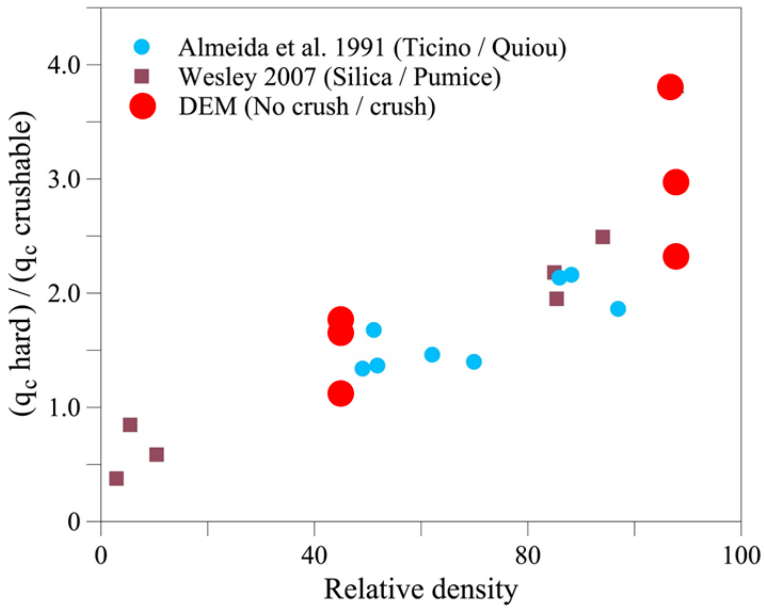

Figure 4: Effect of crushability on cone resistance for different relative densities. Experimental and DEM results

3 PFEM MODELLING OF UNDRAINED CONE PENETRATION IN CLAYS

The continuum modelling of the cone penetration test has been performed using the Particle Finite Element Method, PFEM [14-16]. The method uses a Finite Element approximation to compute the movement of the particles within an updated Lagrangian framework. In this method, particles and nodes coincide and the mesh is updated when required to prevent excessive distortions; Delaunay tessellation is used for this purpose. The mesh nodes are considered particles that carry mass and the state variables and, being particles, they can separate from the main domain giving rise to new boundaries. Although the method was initially developed for fluid-solid interaction problems, there have already been some applications to geotechnical problems [17-19].

Figure 5 shows a scheme of the method that can be summarised in the following steps: i) A cloud of particles, C_n, is defined at a time $t=t_n$, ii) identify the boundaries defining the analysis domain, iii) discretise the domain with a finite element mesh, iv) solve the governing equations within a Lagrangian formulation and compute the state variables at the next updated configuration at t_{n+1}, v) move the nodes to the new position C_{n+1}, vi) go back to step i).

In a purely undrained case the soil can be considered as a single phase medium and only the linear momentum balance equation (equilibrium) needs to be solved. Accordingly, a total-stress Tresca constitutive model has been adopted to represent the soil whereas the tangential contact with the rigid cone has been simulated with a von Mises yield criterion. The analyses presented here have been performed with a rigidly index, Ir = 100. The geometry of the problem and the computation domain are shown in Figure 6a.

The cone penetration analyses have been carried out using values of cone-soil adhesion ratio (α = adhesion/undrained shear strength) ranging from 0 to 0.7. The results in terms of cone penetration (normalized as cone factor N_{kt}) and friction sleeve resistance are plotted in Figure 6b. As expected, the friction sleeve resistance coincides with the specified adhesion and the cone resistance increases modestly with the value of adhesion. Figure 7 shows more explicitly the variation of cone factor with the value of adhesion. The gradient of the variation of the cone factor as roughness increases is 1.8; this value is within the range of other analyses.

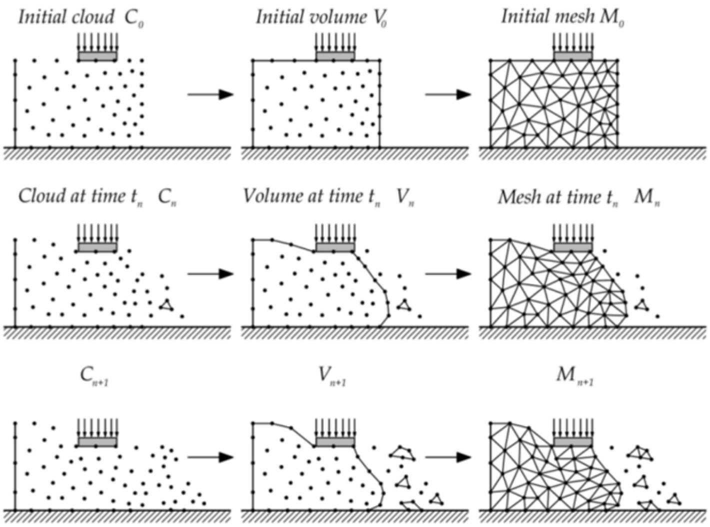

Figure 5: Scheme of a PFEM computational step

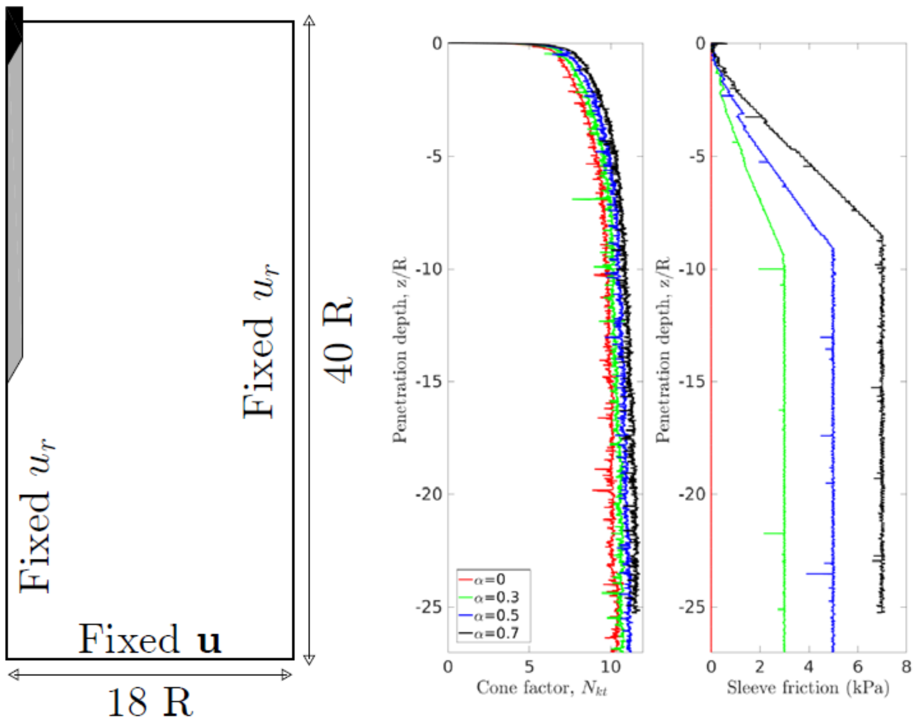

Figure 6: a) Geometry and computational domain of the PFEM analysis of cone penetration. b) Cone factor and friction sleeve resistance for different values of adhesion

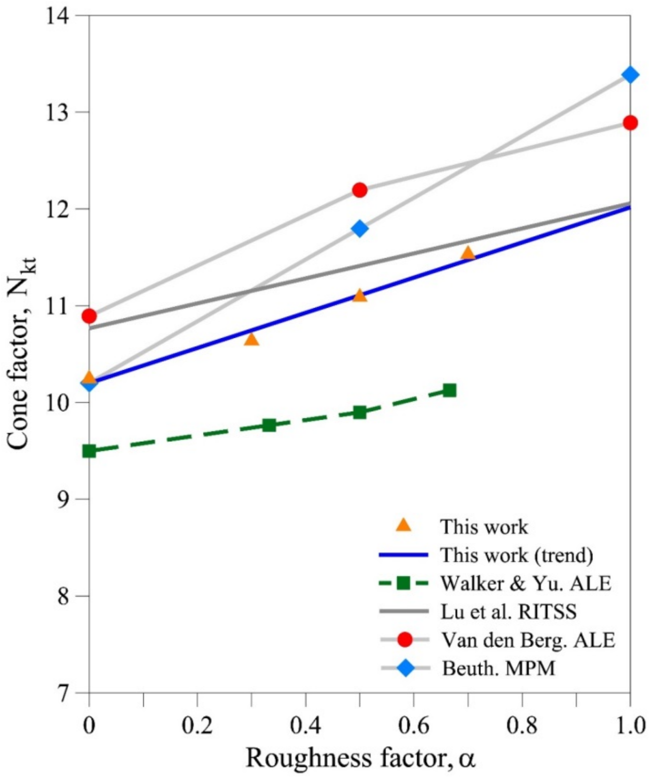

Figure 7: Influence of contact roughness on cone factor N_{kt}

To illustrate further the performance of the method, Figure 8 shows the PFEM meshes (and mean stress contours) at the start and the end of the analysis. It can be readily noted how the mesh refinement has adapted to the advance of the cone accommodating, without undue element distortions, the large displacements associated with the penetration of the cone. More information on this analysis is given in [20].

4 CONCLUDING REMARKS

Two different approaches have been presented for the modelling of the cone penetration test that attempt to overcome the considerable difficulties associated with the simulation of penetration problems, i.e. large displacements, large strains and rotations, severe domain distortion as well as geometrical, material and contact nonlinearities. Both the DEM and PFEM procedures have shown their capabilities in this respect although some significant challenges and shortcomings remain. They constitute, however, areas of intense development and research that should lead to an increasingly realistic description of the process of cone penetration in all its complexity. Consequently, it can be envisaged that more rational-based procedures for the interpretation of the test should ensue. More generally, these numerical procedures open up the prospect of efficient simulations of a wide range of penetration problems in geomechanics.

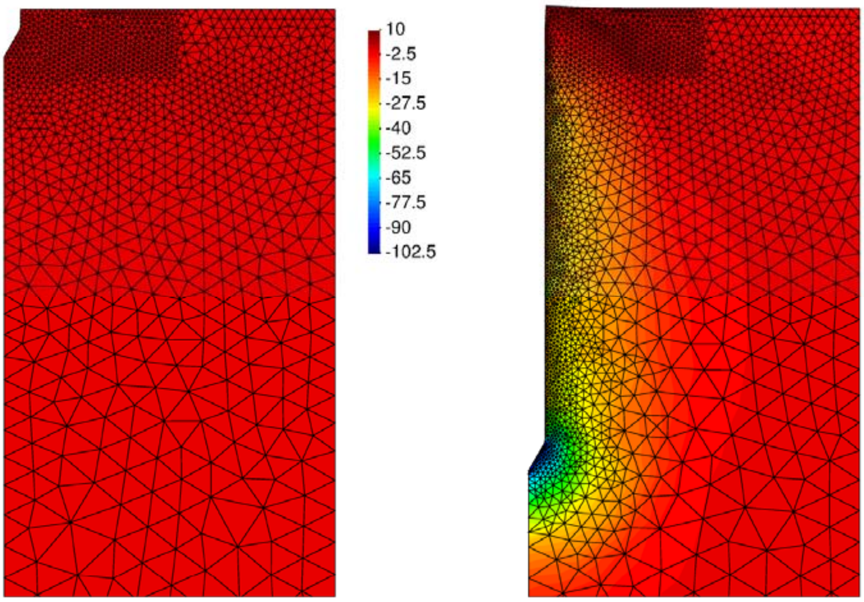

Figure 8: PFEM meshes and mean stress contours at the start (left) and at the end (right) oh the analysis

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REFERENCES

[1] Gens, A., Arroyo, M., Butlanska, J., Carbonell, J.M., Ciantia, M., Monforte, L. and O'Sullivan, C. Simulation of the cone penetration test: discrete and continuum approaches. *Australian Geomechanics* (2016) **51**(4):169-182.

[2] Cundall, P. A. and Strack, O. D. L.. Discrete numerical model for granular assemblies. *Géotechnique* (1979) **29**(1): 47-65.

[3] O'Sullivan, C. *Particle-Based Discrete Element Model-ing: A geomechanics perspective.* Hoboken, NJ: Taylor & Francis (2011).

[4] Almeida, M., Jamiolkowski, M. and Peterson, R.. Preliminary results of CPT tests in calcareous Quiou sand. *Proceedings of the International Symposium on Calibration Chamber Testing*: 41-53. New York: Elsevier (1991).

[5] Ahmed, S. M., Agaiby, S. W. and Abdel-Rahman, A. H. A unified CPT–SPT correlation for non-crushable and crushable cohesionless soils. Ain Shams Engineering Journal (2014) **5**: 63-73

[6] Moss, R.E.S. A Critical State framework for seismic soil liquefaction triggering using CPT, *3rd International Symposium on Cone Penetration Testing, CPT14*, Las Vegas, Nevada, Paper 2#20 (2014).

[7] Wesley L. D. Geotechnical characteristics of a pumice sand. In Tan et al. (ed.) *Characterisation and Engineering properties of Natural Soils*: 2449-2473. London: Taylor & Francis (2007).

[8] Ciantia, M. O., Arroyo, M., Butlanska, J. and Gens, A. DEM modelling of a double-

porosity crushable granular material. In K. Soga et al. (Ed.), *Proc. Int. Symp. on Geomechanics from Micro to Macro*: 269-274. London: Taylor & Francis (2014.
[9] Ciantia, M. O., Arroyo, M., Calvetti, F. and Gens, A. An approach to enhance efficiency of DEM modelling of soils with crushable grains. *Géotechnique* (2015) **65**: 91–110.
[10] Russell, A. R. and Muir Wood, D. Point load tests and strength measurements for brittle spheres. *Int. J. of Rock Mech. and Mining Sciences* (2009) **46:** 272–280
[11] Russell, A. R., Muir Wood, D. and Kikumoto, M.. Crushing of particles in idealised granular assemblies. J. Mech. Phys. Solids (2009) **57**: 1293–1313.
[12] Arroyo, M., Butlanska, J., Gens, A., Calvetti, F., and Jamiolkowski, M. Cone penetration tests in a virtual calibration chamber. *Géotechnique* (2011) **61**: 525-531.
[13] Ciantia, M. O., Arroyo, M., Butlanska, J. and Gens, A. DEM modelling of cone penetration test in a double-porosity crushable granular material. *Computers and Geotechnics*. (2016) **73**:109-127.
[14] Idelsohn, S.R., Onate, E. and Del Pin, F. The particle finite element method: a powerful tool to solve incompressible flows with free-surfaces and breaking waves. *Int J Numer Meth Eng.* (2004) **61**:964–89.
[15] Onate, E., Idelsohn, S.R., Del Pin, F. and Aubry, R. The particle finite element method an overview. *Int J Comput Meth*. (2004) **1**:267–307.
[16] Carbonell, J.M.. *Modeling of ground excavation with the Particle Finite Element Method*. Ph.D. Thesis. Universitat Politècnica de Catalunya, Barcelona (2009).
[17] Carbonell J.M., Onate, E. and Suarez, B. Modeling of ground excavation with the Particle Finite Element Method. *Journal of Engineering Mechanics, ASCE* (2010) **136**: 455-463.
[18] Zhang, X., Krabbenhoft, K., Pedroso D.M., Lyamin, A.V., Sheng, D., da Silva, M.V. and Wang, D. Particle finite element analysis of large deformation and granular flow problems. *Computers and Geotechnics* (2013) **54**: 133-142.
[19] Zhang, X., Krabbenhoft, K., Sheng, D. and Li., W. Numerical simulation of a flow-like landslide using the particle finite element method. *Computational Mechanics* (2015) **55**: 167-177.
[20] Monforte, L., Arroyo, A., Carbonell J.M. and Gens A. Numerical simulation of undrained insertion problems in geotechnical engineering with the Particle Finite Element Method (PFEM) Computers and Geotechnics (2017) **82**: 144-156.