# Discrete Element simulations of penetration mechanics in granular media

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## INTRODUCTION & OBJECTIVES

The exploration of soil through perforation has been used extensively in many human and industrial activities: agriculture, construction, extraction of natural resources (water, oil, natural gas, etc.), archeology, geophysics, etc. Also Nature makes use of soil penetration, especially in plant growth. Therefore, the study of the penetration mechanics in granular media is of extreme importance both to better understand natural phenomena and to optimize soil exploration activities.

Here we present numerical simulations based on the Discrete Element Method (DEM) of the penetration of different probe geometries in a granular packing. The objective of the present research is to evaluate the penetration performance (in terms of penetration force or expended work) of different geometries and thus to propose an optimized design with improved efficiency.

## RESULTS

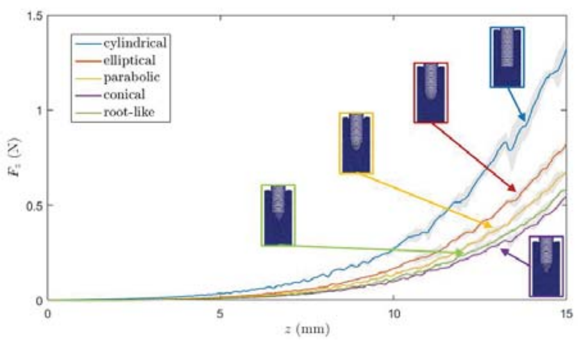
The DEM simulations were carried out in the Open Source Software LIGGGHTS® 3.6.0. Each simulation was divided into two steps:

1. the random packing of a monodisperse distribution of spherical particles, under the action of gravity;
2. the penetration of the particle packing through a rigid probe moving at a constant velocity.

Five probe geometries were considered: cylindrical, elliptical, parabolic, conical and a root-inspired probe, with a intermediate profile between the conical and the parabolic one.

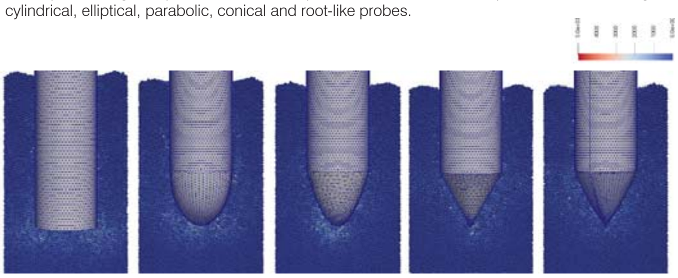
The penetration force vs. penetration depth curves show a clear distinction among the investigated, demonstrating that a conical and a root-like shape are the optimal ones. These findings were confirmed by the expended penetration work data, computed by numerically integrating the force-depth curves, providing a quantitative understanding of the penetration performance.

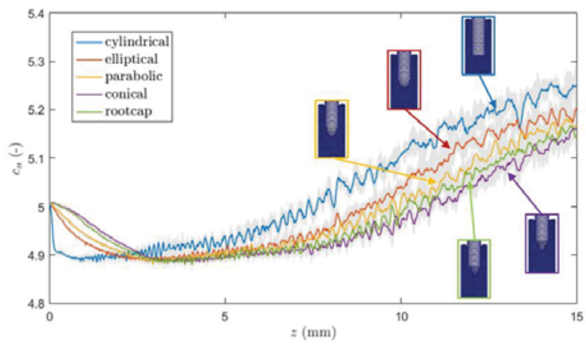
The pictures below show that absolute value of the particle-particle and particle-probe forces drive the whole penetration process and determine the observed penetration force curves (Left). Interistingly, the contact number has emerged to be a key parameter controlling the penetration process: the higher penetration forces are measured also when high values of the contact number are observed, suggesting that also the local density of the granular medium plays an important role (Right).




### PENETRATION FORCE CURVES

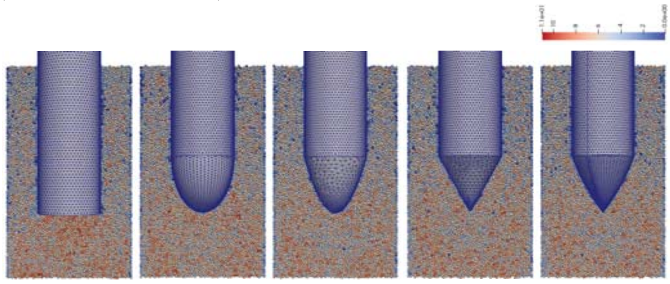
Top: the total vertical force acting on each geometry is plotted as function of the penetration depth. By computing the expended penetration work as $W(z) = \int_0^{z_0} F(z)\mathrm{d}z$, for a depth $z_0 = 15$ mm we get an average value of 4.03, 2.46, 2.01, 1.71 and 1.52 mJ for the cylindrical, elliptical, parabolic, root-like and conical shapes, respectively.
Bottom: the geometry of the probe affects the magnitude of the forces (here in units of $10^{-9}$ N) developed during the penetration, here represented at a 10 mm depth. From Left to Right: cylindrical, elliptical, parabolic, conical and root-like probes.






### CONTACT NUMBER EVOLUTION

The contact number is the average number of particles simultaneously in contact with a central particle and can be related to the local density of the granular medium.
Top: the contact number for each geometry is plotted as function of the penetration depth.
Bottom: the geometry of the probe affects the value of the contact number developed during the penetration, here represented at a 15 mm depth. From Left to Right: cylindrical, elliptical, parabolic, conical and root-like probes.



## CONCLUSIONS

We have shown how computer simulations can provide a deep understanding of pemetration mechanics processes, especially by highlighting the underlying physical mechanisms, thus paving the way towards the engineering of optimal probe geometries.

## ACKNOWLEDGEMENTS

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