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▶ **To cite this version:**

Quoc Anh Tran, Bastien Chevalier, Miguel Benz, Pierre Breul, Roland Gourves. Modeling of light dynamic cone penetration test – Panda 3 ® in granular material by using 3D Discrete element method. Powders and Grains 2017 – 8th International Conference on Micromechanics on Granular Media, 2017, Montpellier, France. 10.1051/epjconf/201714016003 . hal-01658303

HAL Id: hal-01658303
https://uca.hal.science/hal-01658303

Submitted on 7 Dec 2017

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EPJ Web of Conferences **140**, 16003 (2017) DOI: 10.1051/epjconf/201714016003
Powders & Grains 2017

Modeling of light dynamic cone penetration test – Panda 3® in granular material by using 3D Discrete element method

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Abstract. The recent technological developments made on the light dynamic penetration test Panda 3® provide a dynamic load–penetration curve $\sigma_p - s_p$ for each impact. This curve is influenced by the mechanical and physical properties of the investigated granular media. In order to analyze and exploit the load-penetration curve, a numerical model of penetration test using 3D Discrete Element Method is proposed for reproducing tests in dynamic conditions in granular media. All parameters of impact used in this model have at first been calibrated by respecting mechanical and geometrical properties of the hammer and the rod. There is a good agreement between experimental results and the ones obtained from simulations in 2D or 3D. After creating a sample, we will simulate the Panda 3®. It is possible to measure directly the dynamic load–penetration curve occurring at the tip for each impact. Using the force and acceleration measured in the top part of the rod, it is possible to separate the incident and reflected waves and then calculate the tip's load-penetration curve. The load–penetration curve obtained is qualitatively similar with that obtained by experimental tests. In addition, the frequency analysis of the measured signals present also a good compliance with that measured in reality when the tip resistance is qualitatively similar.

1 Introduction

The light dynamic penetrometer with variable energy Panda is widely used to determine the mechanical properties of soils. In the beginning, this device was able to measure only the tip resistance (q_d) for each impact by using the Dutch formula with the kinetic energy measured by the strain gauges placed in the head of the apparatus [1]. In recent years, the latest version - Panda 3® has been developed by Benz [2]. For each impact, we will measure the force $F_A(t)$ and acceleration $A_A(t)$ at the measuring point - (A). Then we are able to rebuild the dynamic load–penetration curve $\sigma_p - s_p$ from these measurements by using the theory of decoupling the waves propagating in the rod [3]. The exploitation of this curve gives us not only the tip resistance (q_d) but also other mechanical parameters of the soil such as the wave velocity, the damping coefficient, the elastic modulus [2].

In order to validate the method applied to the Panda 3® and better understand the mechanism of penetration involved in this kind of test, there are many numerical studies based on Discrete Element Method (DEM) in two dimensions (2D) [2, 4–7].

In this paper, we will present a numerical model in three dimensions (3D) for reproducing Panda 3® test with PFC^{3D} from Itasca [8].

At first, the theory of decoupling waves propagating in the rod will be briefly presented in the section 2. We will talk in detail about the numerical model in the section 3. Then, the section 4 will show some results obtained with the numerical model in order to validate the wave analysis used for Panda 3®. Finally, the values of accelerance ($A/F(\omega)$) obtained by the numerical model and by experimental tests of Panda 3® with similar amplitude of tip resistance ($q_d \approx 2MPa$) are compared.

2 Theory of decoupling of waves propagating in the rod

In this section, we will presents briefly the method of wave separation applied on Panda 3®. For more details about wave theories applied on Panda 3®, the reader can refer to the works of Benz [2].

In order of separate ascending and descending waves in the rod, three assumptions are made: (*i*) the rod is linear elastic; (*ii*) the stress is uniform throughout all of cross-sections; (*ii*) the propagation velocity of wave in the rod does not depend on the frequency [9].

When the hammer of mass M hits the head of the penetrometer with the velocity v_m, a compression wave $u(x,t)$ will be generated and will propagate at constant speed c_{rod} towards the cone by the following equation:

$$\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{1}{c_{rod}^2} \cdot \frac{\partial^2 u(x,t)}{\partial x^2} \tag{1}$$

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Table 1. Micro-parameters used for the contact

Contact Type	$E^*[MPa]$	$\kappa^*[-]$	$\mu[-]$	$\beta_n[-]$
Hammer vs Anvil	305.04	2.7058	0.0	0.0
Rod balls vs Tip	206e3	2.7058	0.0	0.0

The general solution of the Eq.1 is represented by the the superposition of two elementary waves, u_{down} and u_{up}, respectively going down and up.

$$u(x,t)=u_{down}(\xi)+u_{up}(\eta) \tag{2}$$

where $\xi = t - x/c^2_{rod}$ and $\eta = t + x/c^2_{rod}$.

During the wave propagation through the rod, the wave $u(x,t)$ causes in each point x along the rod a deformation $\epsilon(x,t)$ and particle velocity $v(x,t)$ also represented by the superposition of two elementary waves:

$$\begin{aligned}\epsilon(x,t)&=\epsilon_{down}(\xi)+\epsilon_{up}(\eta)\\ v(x,t)&=v_{down}(\xi)+v_{up}(\eta)\end{aligned} \tag{3}$$

By measuring at the point of measure A, located close to the anvil, the deformation $\epsilon(x_A,t)$ and/or acceleration $a(x_A,t)$ for each impact, we are able to describe entirely the dynamic phenomenon in each point x along the rod [2]. We will present in the subsection 4.1 the validation of the theory of wave separation.

3 Numerical Model

We present here first the calibration of the impact in the numerical model, by respecting mechanical and geometrical properties of the hammer and the rod (subsec. 3.1). After creating a sample (subsec. 3.2), we will simulate the penetration test Panda 3® and present the results in the subsection 3.3.

3.1 Calibration of the impact

In order to respect mechanical and geometrical properties of the hammer and the rod [2], the anvil is modeled by a sphere of 3 *cm* in diameter with a mass equal to 0.75 *kg*. The rod is made by a set of contacting spheres of 1.4 *cm* diameter aligned vertically. The length of the rod L_{rod} is first set to 8 *m* in order to cancel the superposition of waves at the measurement point A. The standard hammer is modeled by a sphere of 6 *cm* in diameter with a mass of 1.69 *kg*.

A linear model was used for the contact between the hammer and the anvil. Contact bond was used to model the contact inbetween rod spheres and between rod spheres and the tip. The table 1 shows microparameters used for each type of contact where: E^* is the effective modulus, κ^* the stiffness ratio ($\kappa^* = k_n/k_s$) at the contact, μ the friction coefficient and β_n the normal critical damping ratio.

Figure 1 shows the evolution of impact force measured at the measurement point A versus time for different impact velocities V_I. The impact duration is order of about 2.0 *ms*. Note that impact sphere is deleted just after contact loss with the anvil.

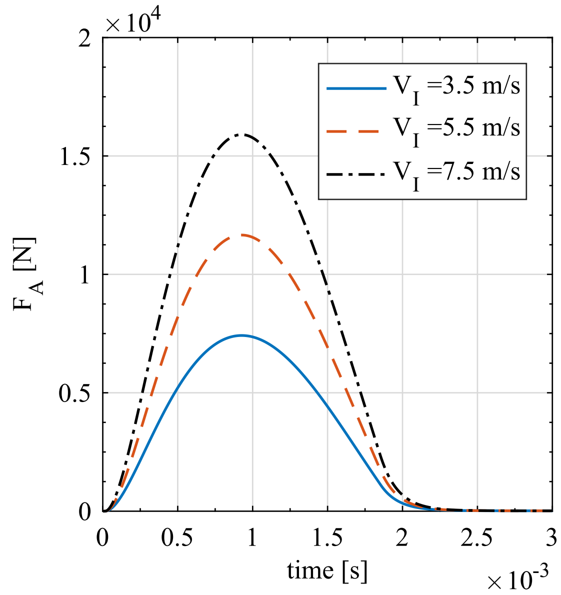

Figure 1. Force F_A at the measuring point A versus time for different impact velocities (V_I) with rod length $L_t = 8m$.

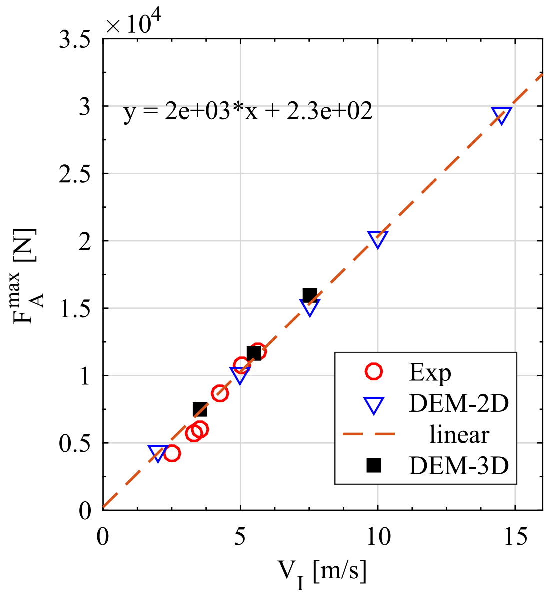

Figure 2. Maximal measured force F_A^{max} obtained by experimental test (○), simulation tests in 2D (▽) [2] and simulation tests in 3D (□).

Figure 2 presents the comparison of the maximal force F_A^{max} at the measurement point A obtained either by the model, the DEM-2D model proposed by Benz, and the experimental test with Panda 3® [2]. The similarity between the three curves is noticeable.

3.2 Sample creation

Once the mechanical and geometrical properties of the hammer are set, the rod and tip can be calibrated. We will

 DOI: 10.1051/epjconf/201714016003

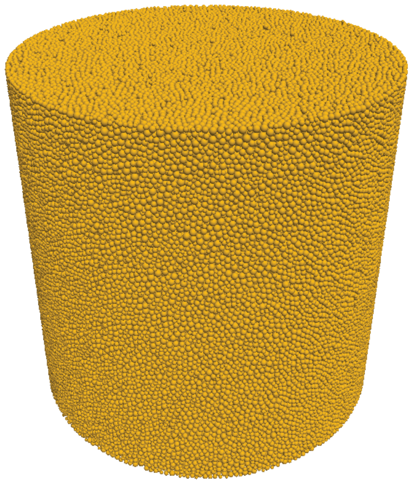

Figure 3. Example of dense assembly of N_p = 389167 particles (D_p^{max} = 0.7cm, R_p^{dia} = 2) in a cylindrical sample with $H_s = D_s$ = 40cm.

Table 2. Micro-pararameters used for the contact involving particles

Contact Type	$E^*[MPa]$	$\kappa^*[-]$	$\mu[-]$	$\beta_n[-]$
Particle vs particle	200	3.3	0.7	0.10
Particle vs rod	200	3.3	0.0	0.00
Particle vs tip	200	3.3	0.3	0.00
Particle vs walls	2	3.3	0.0	0.00

create a sample of particle for simulating the penetration test Panda 3®.

Figure 3 shows an example of dense particle assembly with N_p = 389167 particles in a cylindrical sample with the height H_s and the diameter D_s equal to 40 cm. Particle diameters are distributed uniform in terms of diameters between maximal and minimal diameter presenting a ratio of 2. The maximal particle diameter D_p^{max} is equal to 0.7 cm. Linear contact model is used between particles. The minimal porosity measured at the centre of the sample is 0.36.

The rigidity of sample walls is smaller than the one of particles (Tab. 2) in order to reduce the influence of boundary condition. A vertical confining stress of 40 kPa is maintained constant during the simulation.

The table 2 shows the micro-pararameters used for the contact involving particles.

3.3 Simulation procedure

After creating a particle assembly, the rod and tip will be driven in the sample at first with constant velocity ($V = 1m/s$) until a depth of 15 cm. This penetration rate is much higher than that one used in the standard CPT (V = 2 ± 0.5 cm/s) in order to reduce the calculation time. In addition, we created a cylindrical walls around rod particles in order to avoid contacts between the rod spheres and the particles of the soil which would disturb the propagation of the wave during penetration [2, 4].

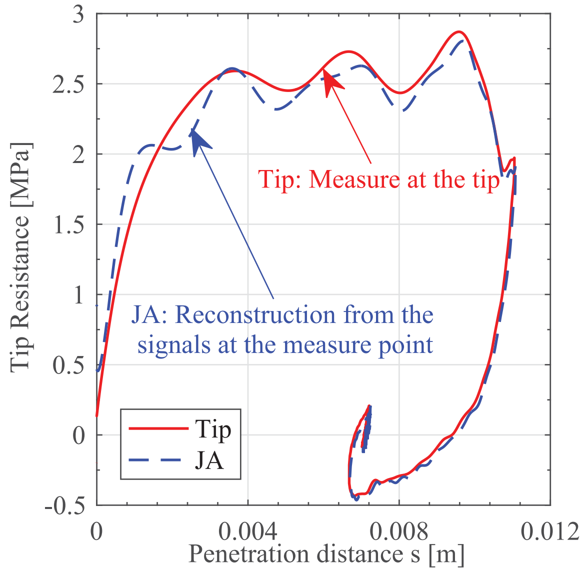

Figure 4. Validation of applied theories on Panda 3®: Tip: tip resistance measured directly at the tip; JA: tip resistance calculated from the force F_A and acceleration Acc_A at the measurement point A

Once the whole system is stabilized, we will create a sphere representing the hammer that will hit the anvil with a velocity of 3.5 m/s.

Some simulation results will be presented in next section for validating the signal processing proposed for the Panda 3® and then exploit the signals obtained in the frequency domain.

4 Simulated results

4.1 Validation of the theory of wave decoupling

Figure 4 shows the load–penetration curve $\sigma_p - s_p$ measured directly at the tip and calculated with the theory of wave decoupling presented before. The good conformity between the two curves demonstrates the relevance of the decoupling theory applied on Panda 3® test results.

4.2 Exploitation of measured signals

In order to determine the mechanic properties of granular materials, Escobar proposed to analyse in the frequency domain the measured signals obtaining by Panda 3® [5]. Despite it is difficult to compare between numerical and experimental results, we present here a qualitative comparison of the properties measured when the tip resistance is comparable ($q_d \approx 2MPa$).

In the frequency domain, the accelerance curve $A/F(\omega)$ is the ratio between the Fourier transform amplitude of accelaration - $|A(\omega)|$ and the one of force $|F(\omega)|$, at the measurement point A [5],

$$A/F(\omega) = \frac{|A(\omega)|}{|F(\omega)|} \tag{4}$$

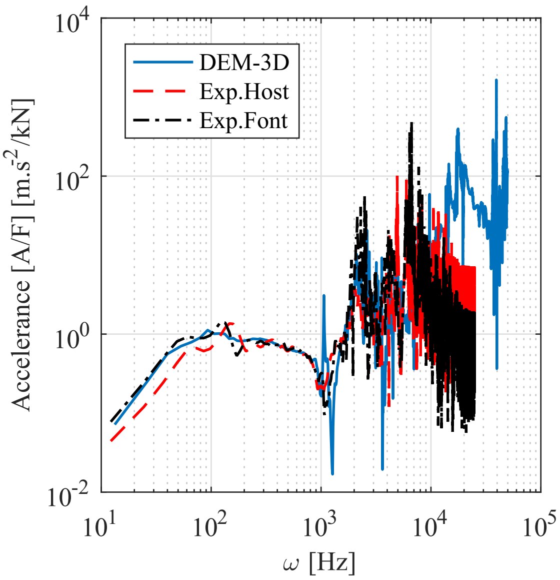

Figure 5. Comparaison of accelerance curve $A/F(\omega)$ obtainted by the numerical model (DEM-3D) and by experimental tests of Panda 3® for Hostun (Exp.Host) and Fontainebleau sands (Exp.Font) for tip resistance values around 2 MPa

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Figure 5 presents the accelerance versus frequency obtainted with numerical model and with experimental tests of Panda 3® for Hostun and Fontainebleau sands. There is a good agreement between these curves when frequency is smaller than 1000 Hz. It shows that the numerical model is able to properly simulate the dynamic penetration test on granular media.

5 Conclusion

We have presented in this paper the simulation of the light dynamic penetration test Panda 3® by using the DEM in 3D in order to validate the methods of analysis proposed for the Panda 3®. A qualitative comparaison of the values of accelerance in the frequency domain showed a good correspondence between numerical and experimental results. It means that the numerical model presented is able to properly simulate dynamic penetration tests in granular media.

It would be interesting to study the mechanisms of penetration and to establish a relationship between the micromechanical parameters of the modeled soil and the mechanical parameters obtained by the signals measured by Panda 3®.

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