Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-1-0

In-situ determination of soil deformation modulus and the wave velocity parameters using the Panda 3®

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ABSTRACT: This article, after a brief reminder of the principle and the interpretation of Panda 3®, present the results of a test campaign on an experimental field. The aim is to achieve in-situ comparative tests to study the relationship between the results obtained with this new measurement technique (elastic modulus, wave velocity, dynamic cone resistance) and those proposed by other classical geotechnical techniques (CPTu, PMT, MASW ...). The results show the potential and interest of this new investigation technique for the characterization of surface soil (depth less than 7 m). Likewise, we find that the response of the load-penetration curve may vary depending on the conditions of the inspected ground (nature, compactness ...). The test allows a more refined geomechanical characterization of the stratigraphy of the soil.

1 INTRODUCTION

Predicting the pre-failure behavior of soils plays an important role in geotechnical studies. This requires a reliable estimation of the deformation characteristics of geomaterials. The determination of the elastic parameters, including the deformation modulus and the wave velocity is extremely important. Currently the in-situ techniques allowing to obtain these parameters are the pressuremeter test (PMT), the flat dilatometer test (DMT), the surface wave method (SWM)… However, these methods only provide discontinuous soil profile. This considered, it seems important to develop ad hoc measurement techniques allowing a continuous study of these parameters according to depth. Furthermore, recent research work on the Panda 3 investigation technique allowed obtaining, for each impact, a load-penetration curve of the inspected soil. The interpretation of this curve allows estimation of the deformation parameters and the wave velocity in the soil.

This article, after a brief reminder of the principle and the interpretation method of Panda 3, present the results of a test campaign on an experimental field. The aim is to achieve in-situ comparative tests to study the relationship between the results obtained with this new measurement technique (elastic modulus, wave velocity, dynamic cone resistance) and those proposed by other classical geotechnical techniques (CPTu, PMT, MASW ...).

2 THE INSTRUMENTED DYNAMIC PENETROMETER PANDA 3®

The Panda 3 penetrometer has been designed based on the penetrometer Panda® (Gourvès, 1991). The principle of the test is simple (Fig. 1): during driving, we measure on the rods, near the anvil, the variation of the deformation $\varepsilon(x,t)$ and/or acceleration $a(x,t)$ caused by the compressional wave created by the impact. For each impact, after decoupling descending ε_d and ascending wave ε_r it is possible to calculate the penetration $s_p(t)$ and the resulting force $F_p(t)$ at the tip during penetration of the cone. By making some simplifying assumptions (Escobar, 2015), it is also possible to plot the dynamic load-penetration curve σ_p-s_p for each hammer impact (Fig. 1c).

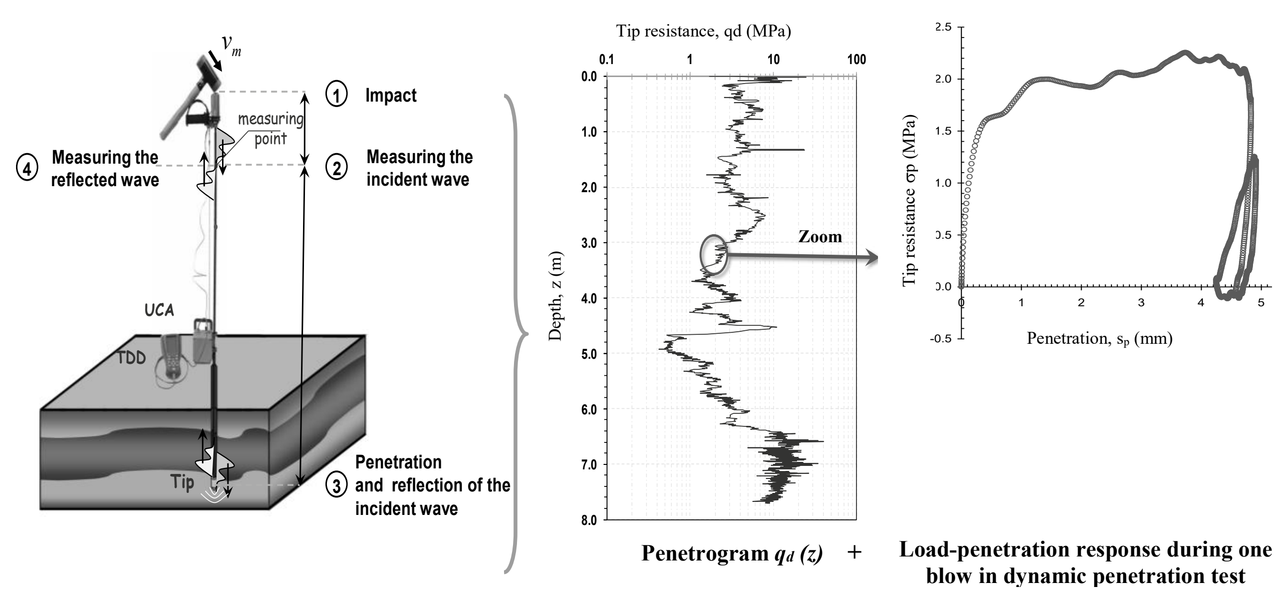

Figure 1. Principle of the Panda 3®: (a) wave propagation, (b) the penetrogram of tip resistance qd and (c) load-penetration curve at the tip σ_p-s_p.

An analytical methodology permits to exploit this curve to determine different soil parameters such as: penetration resistance q_d and q_c, the dynamic stiffness E_{kd}^{P3}, the deformation modulus E_d^{P3} and the wave velocity in the soil V_p^{P3} (Benz et al, 2013). A summary of the operating parameters from the time and frequency analysis of the signals recorded during driving is presented in the following chapter.

2.1 *Strength parameters*

An analytical methodology for the interpretation of the σ_p-s_p curve was proposed by Smith (1960). Assuming that the tip resistance $q_d(t)$ is the resultant of:

static component R_s, which obeys an elastic-perfectly plastic law, and

dynamic component $R_d(t)$,which is proportional to the velocity of the penetration $v_p(t)$;

We determine the value of R_s supposing that when $v_p(t)$ equals zero the dynamic component $R_d(t)$ cancels itself out and R_s is then equal to $q_d(t)$. The values of $R_d(t)$ and the dampening ratio of Smith J_s are determined in the penetration interval [s_e; s_{max}], with s_e and s_{max} being the elastic and maximum penetration and writing that $R_d(t) = q_d(t) - R_s$ and $J_s = R_d(t)/(R_s v_p(t))$ (Fig. 2.a).

2.2 *Deformation parameters*

Once the maximum penetration s_{max} is reached, we assumed that soil and the penetrometer vibrate together in a pseudo-elastic regime. In this part of the σ_p-s_p, curve, two modules are defined as: an unloading module E_d^{P3} (line AB) and a reloading module E_r^{P3} (line BC) (Fig.2.a). Supposing that the cone is a small plate embedded in a semi-infinite elastic solid we can calculate the value of $E_{d,r}^{P3}$ by applying the equation of Boussinesq (1) proposed by Arbaoui, (2006).

$$E_{d'r}^{p3} = (1-\mu^2)\frac{\Delta q_d}{\Delta s_p}\frac{\pi d_p}{4}\frac{1}{k_M} \qquad (1)$$

With μ the Poisson's ratio supposed equal to 0,33, d_p the diameter of the cone and k_M the coefficient of embedding of Mindlin (Arbaoui, 2006).

2.3 *Dynamic stiffness*

Another method to exploit the signals recorded during driving of Panda 3 penetrometer is one proposed by Paquet (1968). In fact, the shock wave caused by the impact of the hammer and vibration of system penetrometer/soil can be described by determining the impedance. This is obtained by conventional methods of the Fourier transform to obtain the transfer functions, and thus drawing the mobility curve (Fig.2.b). Moreover, according to Caballero (2007) it is possible to estimate the dynamic stiffness K_d^{P3} for the frequency range between 0 and 100 Hz. Similarly, assuming the cone penetrometer is a small plate in a semi-infinite elastic medium, it is possible; through the expression proposed by Boussinesq to calculate the deformation module E_{kd}^{P3} at low-frequency according to the expressions (2) and (3).

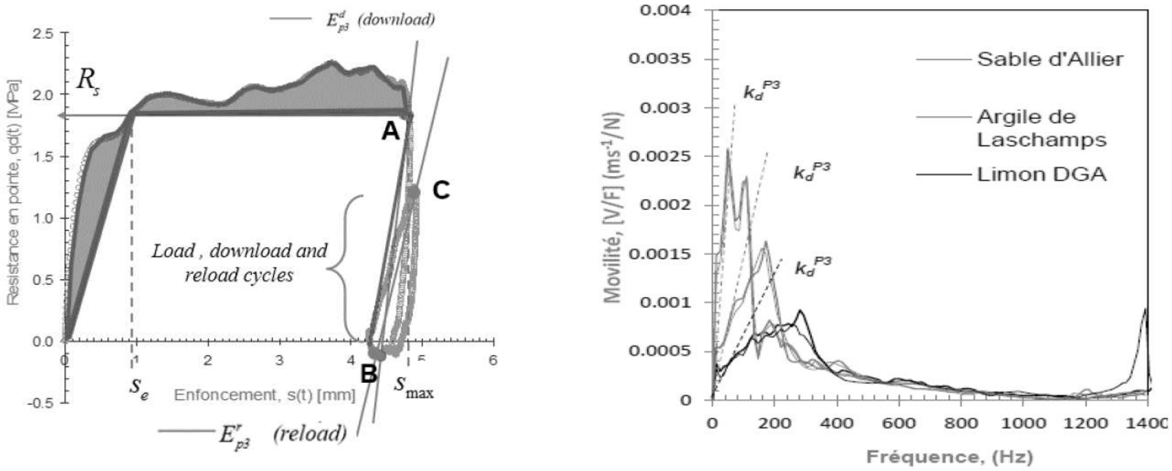

Figure 2. Interpretation of the signals recorded during the driving from the time and frequency analysis: (a) analytical model of interaction cone/soil [4] and (b) mobility curves obtained in the laboratory for different materials (Allier sand, Laschamps clay and DGA Silt)

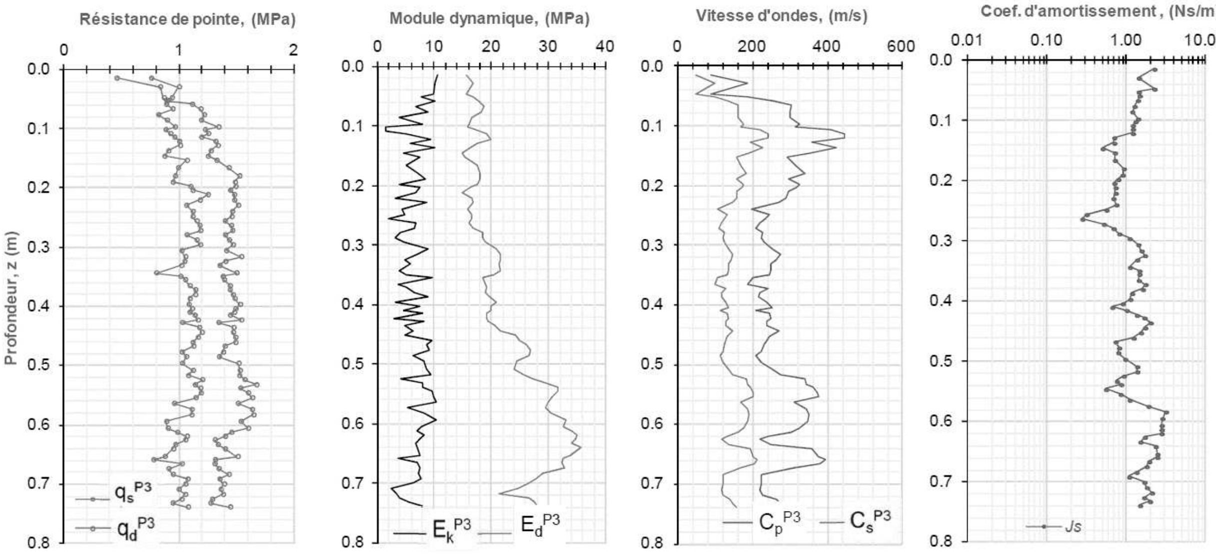

Figure 3. Panda 3® results obtained in a calibration chamber for Laschamps clay. Penetrogram of: (a) tip resistance q_d et q_c, (b) dynamic stiffness E_{kd}^{P3} and deformation modulus E_d^{P3}, (c) the shear and compressional waves celerity V_s^{P3} et V_p^{P3} and (d) damping coefficient J_s.

$$K_d^{P3} = 2\pi \frac{\Delta\omega}{\Delta M} \qquad (2)$$

$$E_{Kd}^{P3} = \frac{\left(1-\mu^2\right)}{\phi_p} K_d^{P3} \qquad (3)$$

With K_d^{P3} the dynamic stiffness determined from the transfer curves, $\Delta\omega$ the frequency variation and ΔM variation of mobility in the frequency range between 0 and 100 Hz, µ Poisson's ratio (0,33) and the ϕ_p the diameter of the cone.

2.4 *Waves velocity*

The compressional wave velocity V_p^{P3} in the soil is calculated through polar shock suggested by Aussedat (1970). For each impact we measure the peaks of the descending and ascending waves in a time t_o+2L_t/c_t. The value of the shear wave celerity c_s^{P3} is calculated according to the expression (4) assuming that the value of μ equals 0,45 at dynamic compression conditions.

$$V_s^{P3} = \sqrt{\frac{1-2\mu}{2(1-\mu)}} V_p^{P3} \qquad (4)$$

In the practice, at the end of one penetration test, we obtained the penetrograms curves of the dynamic q_d and pseudo-static q_s resistance, dynamic stiffness E_{kd}^{P3}, deformation modulus E_d^{P3}, the shear and compressional waves velocity (V_p^{P3} and V_s^{P3}) and a damping coefficient J_s (Fig. 3). Numerous tests were conducted in a calibration chamber to validate the feasibility of this technique (Benz et al. 2013), as well as a numerical model of dynamic cone penetration test in granular media (Escobar et al. 2013).

To show the interest of this new auscultation technique, one experimental champagne is submitted to tests. Those tests are briefly described in the following chapter.

3 EXPERIMENTAL CAMPAIGN

The tests were realized on an experimental site in the commune of Gerzat (Puy-de-Dôme, France). The soil has mainly clay-marl formation. This site was subjected to the geotechnical survey by different techniques (CPTu, MASW, Pressiometer PMT, Panda 2…).

The interest of performing tests with Panda 3 on these sites, in addition to validate the obtained results, is to study the repeatability and measurement sensitivity subjected to variations related to the characteristics of the soil mentioned above. Indeed, the soil in the commune of Gerzat as an embankment has a rather great heterogeneity regarding the nature and condition of these soils.

3.1 *Panda 3 results*

In these experiments we studied the feasibility of field tests which allow validating the repeatability and quality of measurements with the Panda 3. Among the results obtained from analysing the signals and load-penetration curves which are previously presented, the characterization of the failure behaviour and stiffness using the dynamic resistance measures of the tip q_d, and dynamic stiffness E_{Kd}^{P3}, as well as the shear waves velocity V_s^{P3} are of particular interest. The experiments shown that the value of the shaft friction on the cone rod mobilized during driving was negligible. This was estimated qualitatively rotating the rod every meter.

Figure 4 presents the results obtained with Panda 3 plotted in function of the depth of tip resistance, the deformation modulus and shear wave velocity. Similarly, a graphical representation of various soil layers is shown on the right of Figure 4. Two surveys were conducted using Panda 3 where reached depth was approximately 6.50 m. It is possible to notice the sensitivity of the measurements obtained according to encountered ground.

Figure 5 presents some examples of load-penetration curves σ_p-s_p obtained for different impacts and different layers of auscultated soil. In order to facilitate understanding and comparison of these curves, values of tip resistance σ_p and the penetration s_p were normalized by their maximum values σ_{max} and s_{max}. It is observed that the shape of σ_p-s_p curve is very repetitive for the same material and is different for the other soil layers. Similarly, the shape of these curves varies with changes in soil conditions (density, moisture...), thereby identifying stress-strain behavior of different soil.

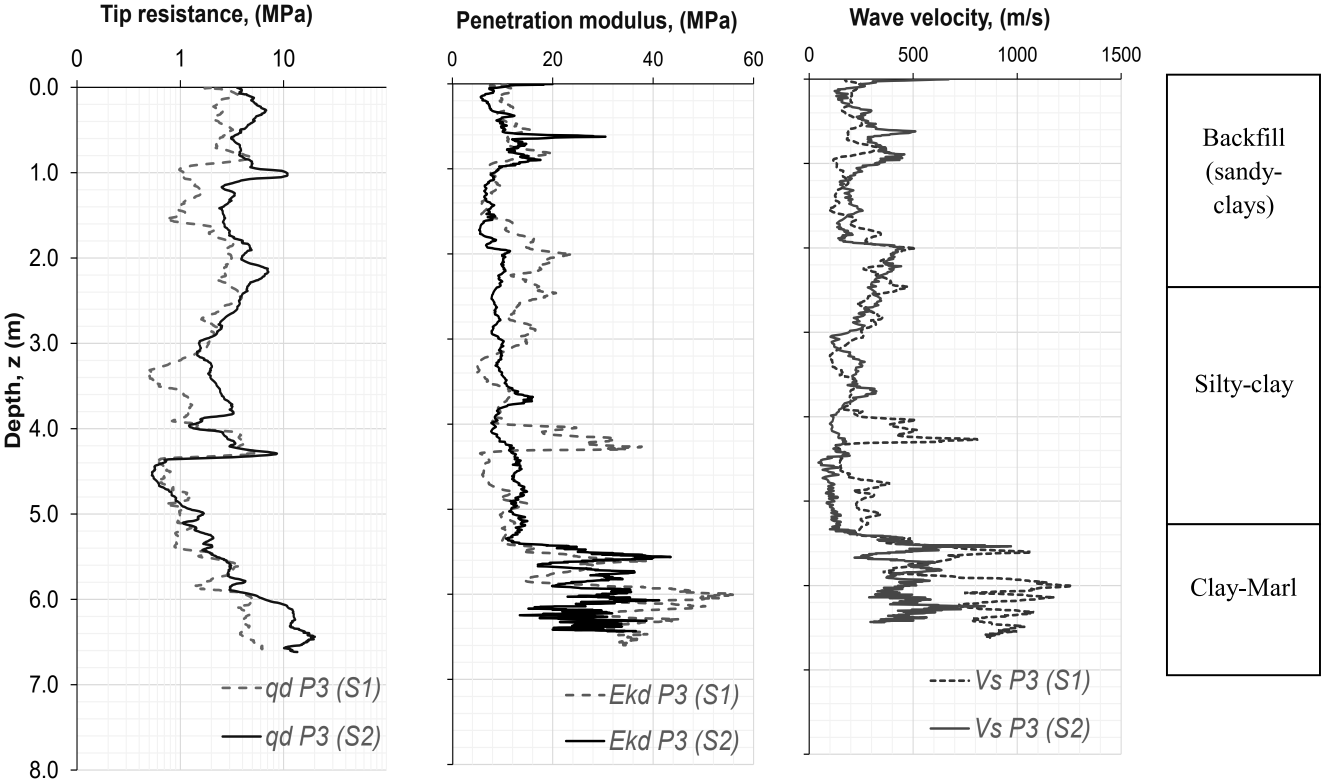

Figure 4. Repeatability of measurements: (a) dynamic tip resistance q_d^{P3}, (b) penetrometer modulus Ek_d^{P3}, (c) shear waves velocity V_s^{P3} – (Gerzat site).

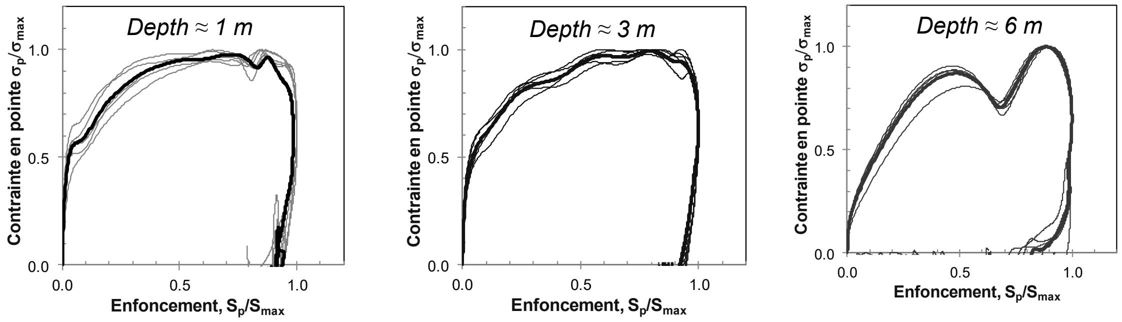

Figure 5. Standardized load penetration curves obtained in Gerzat for different soil layers: (a) Sandy clay, (b) Silty clay and (c) Marl clay (compact). Panda 3 survey.

3.2 *Comparison results*

In the following is provided the comparison of results obtained with the Panda 3 (strength, modulus, wave velocity) with those obtained by using other techniques (geophysical MASW, penetrometer CPTu, Panda 2 and Pressuremeter PMT).

Figure 6.a presents the superposition of penetrograms *qd* (Panda 2), *qd* (Panda 3) and *qc* (CPTu). Despite the high variability in the first auscultated meter on this experimental site it is possible to observe a very good reproducibility between the obtained signals.

Figure 6.b shows the superposition of two tests conducted with Panda 3 and one pressuremeter test. It is possible to notice that the values of the pressuremeter modulus are naturally smoother than those obtained with the penetrometer Panda 3. Indeed, Pressuremeter tests were carried out by steps of 1m and the results obtained for each measurement level, incorporate a soil volume much greater. However, measurements with Panda 3, are carried out ad hoc, with average penetration of 10mm, allowing to highlight the variability of soil and to identify either the singular points or passage of different layers.

Despite the effects of discreet character of the measurement that Panda 3 may have on the comparison of data, it is possible to notice the good match between these values.

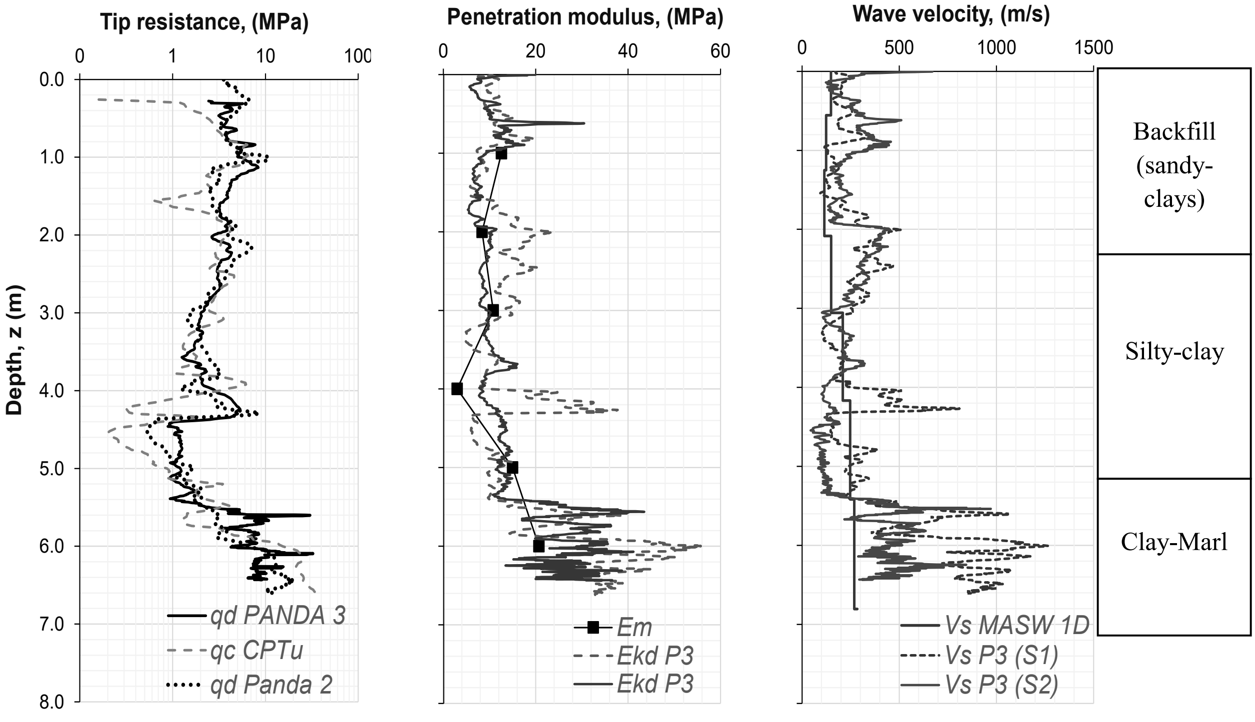

Figure 6. Comparative tests between: (a) the cone resistance qc CPTu vs dynamic tip resistance qd Panda 3 and qd Panda 2, (b) penetrometer modulus Ek_d^{P3} vs pressuremeter modulus Em et (c) shear wave velocity V_s^{P3} vs the shear wave velocity of the seismic method MASW 1D.

Figure 6.c shows the results obtained in terms of shear wave velocity. It is observed that superposition of obtained curves follows the same velocity as the shear wave velocity of the seismic method V_s. However there are occasional passages where the results obtained using Panda 3 and seismic measurement MASW 1D are less compatible. This could be explained by the integrative character of the seismic method which takes into account a large volume of soil and tends to homogenize the results

Table 1 presents a summary overview of the results for each auscultated soil layer presented in the preceding paragraphs. The results thus presented correspond to the average values for each parameter and for each soil layer.

Table 1. Summary of Panda 3® results for each soil layer identified along the survey

	Layer 1	Layer 2	Layer 3
Nature	Backfill (sandy clays)	silty clay	Clay Marl
deep, z (m)	(0,0 – 2,4)	(2,4 – 5,2)	(z > 5,2)
qd P3 (MPa)	2,6	2,5	9,4
qd P2(MPa)	3,5	2,7	10,5
qc CPTu(MPa)	3,1	2,1	17,0
EkdP3 (MPa)	9,2	11,0	27,0
Em PMT(MPa)	10,2	9,6	20,7
Vs P3 (m/s)	235	231	421
Vs MASW (m/s)	132	212	308

4 CONCLUSION

This article presents the recent developments made on the Panda 3 penetrometer in order to characterize the geomechanical behaviour of the soil auscultated. The test allows, from the measurement and the decoupling of waves created by the impact, to obtain for each impact a load-penetration σ_p-s_p curve of the tested soil. The exploitation of this curve permits to determine the resistance parameters (cone resistance q_d and q_c), deformation (E_{kd}^{P3} and E_d^{P3}), damping characteristics (J_s) and wave velocity of soils (V_p^{P3} and V_s^{P3}) inspected in function of the depth throughout the survey.

The realization of these experimental campaign allowed us to demonstrate their feasibility and identify different usage limitations in the current state of development (maximum auscultation depth 6,0m for compact soils). Similarly, we could identify the richness of continuous information on each load-penetration curve obtained during penetrometer driving. Indeed, the Panda 3 tests were able to provide measurements up to 6-7 m depth in most cases and identify singularities and transitions layers that other techniques fail to highlight. The results are highly satisfactory both qualitatively and quantitatively.

Furthermore, regarding the results provided by the test, it is observed that there is good correspondence between the results (tip resistance, deformation modulus and shear wave velocity) with those obtained using "conventional" tests, namely MASW method, pressuremeter PMT, Panda 2® and the piezocone test CPTu. This technique would allow engineers to provide satisfactory data for predicting the pre-failure behavior of soils for geotechnical studies.

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