Correlation between static (CPT) and dynamic variable energy (Panda) cone penetration tests

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ABSTRACT: Dynamic penetrometer is a worldwide practice in geotechnical exploration and Panda lightweight variable energy is the most developed device nowadays. Widely used in France, in Europe and other countries, Panda remains unknown. This paper presents the Panda test and the main goal is to establish an empirical correlation between dynamic variable energy penetrometer (Panda) and cone penetration test CPT. This study is based on about 100 comparative tests performed the last 20 years around the world. In order to demonstrate the good agreement obtained as well as to complete comparative database, an experimental campaign, carried out recently in France, is presented. A general correlation and qc model prediction is proposed.

Keywords: In-situ test, Penetrometer, Correlation, Panda, DPT, CPT.

1. Cone penetration testing

Among the wide range of in situ geotechnical tests currently available, dynamic penetration tests (DPT) are the most commonly used for soil characterization around the world. Due to its rapid implementation, affordability and suitability for most soil types, DPT are present in current geotechnical practice in many countries. This technique is certainly the oldest one technique for geotechnical soil characterization [1]. The first known experiences of the DPT date back to the 17^{th} century in Europe and one of the first known registers is that of Goldmann in 1699 [2], where dynamic penetrometer is described as a method of hammering a rod with a conical tip where penetration per blow can be recorded to find differences in the soil stratigraphy. At the beginning of the 20^{th} century, the first major development of the device also took place in Germany with the development of a lightweight dynamic penetrometer known today as the "Künzel Prüfstab" [3] and standardized in 1964 as the "Light Penetrometer Method" (Figure 1).

With the European development of DPT and because of the simplicity of the technique, many developments have taken place throughout the world. Scala [4] developped in Australia the Scala dynamic penetrometer, which has been widely used for design and quality control of pavement and shallow foundation. Sowers and Hedges [5] developed the Sowers penetrometer, for in-situ soil exploration and to assess the bearing capacity of shallow loaded footings. Webster et al. [6] and the US Army Corps of engineers, has developped the dual mass DCP, well known in North America. Recently, Sabtan and Shehata develops in 1994 the Mackintosh probe [7]

The low driving energy and limited probing depth offered by light dynamic penetrometer, caused the development of heavier devices, like SPT and Borros, in Europe and USA. Several generations of DPTs have followed one another and we can find today a wide variety [8]. Characteristics and use are described in the standard (ISO 22476-2). Despite the wide variety of DPTs developed the last century, the mean principle, the equipment and technology associated remains the same as that described by Goldmann in 1699 and not changed much since the "Künzel Prüfstab" in 1936. In fact, in contrast to the cone penetration test (CPT), which has undergone significant technological development, and has gained in popularity the last fourty years [9], [10]; DPT stayed away from these advances and remain associated with old and rudimentary technology.

It was only at the end of the 1980s that the first major improvements took place. In France, R. Gourvès [11] developed the first instrumented dynamic variable energy penetrometer: the Panda® (Figure 1.b-c). A general description of Panda test, as well as the results obtained will be given in the section (see §3)

Furthermore, cone penetration testing (CPT) is a relatively recent geotechnical field investigation method, but which has become very popular during the last four decades. In fact, in comparison to the DPT, the measurement concept to asses the strength resistance of soils by pushing a cone into the soil was developped early, between 1920-1950, and it was initially P. Barentsen in 1930 who invented the Dutch cone penetrometer [12]. Since 1950 the developpements and technology associated with CPT have been increased. The evolution of modern CPT test has been quick for the last decades and actually there are a large number of electrical cones that associate not only strain or pressure sensors, but also accelerometrrs, inclinometers, visio-cameras, geophones…

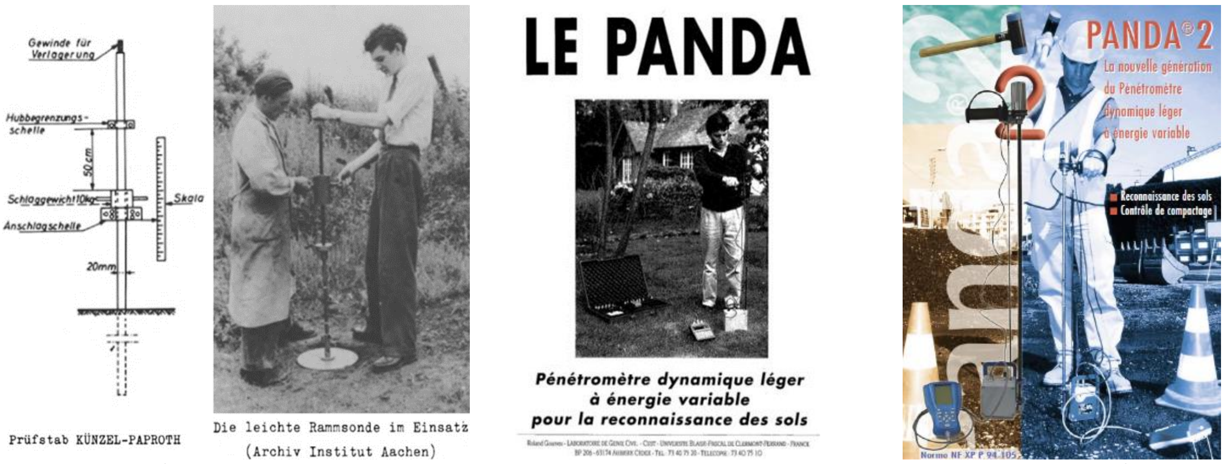

Figure 1. (a) Prüfstab Künzel-Paproth" (Menzenbach, 1959) (b) Panda® lightweight dynamic variable energy penetrometer: first generation (Gourvès R. , 1991) and (c) Panda 2®: second generation.

Unlike DPT test, at the present a large number of references are available discribing detailed technical, practical and technological topics of CPT as well as interpretation and geotechnical explode of the results obtained (i.e.:[9], [13]).

In Europe, both electrical or piezocone CPT test, are currently referenced by the standard (ISO 22476-1). Indeed, currently feedback of experiences (in-situ or laboratory), test databases as well as litterature references availables and which allow to evaluate state, stress-strain paramaters of soils from *qc* value are large and exhaustive [9], [13]–[15].

Undoubtedly cone penetration tests, dynamic (DPT) or static (CPT), is the most worldwide used tool for soil characterization. Notwithstanding its geometrical similarities, the main difference (*beyond technicity, equipment investment, transport, accessibility, implementation time… as well as the total cost of each test*) lies the ways of conical tip is introducing into the soil. Thus, geotechnical engineers distrust of the dynamic penetration, precisely because of its dynamic nature.

Although current theories and instrumentation allow to improve the interpretation of the dynamic test, very few studies have been made in order to improve cone dynamic penetration test (DPT) as well as to its correlation relationship with cone static test (CPT).

Assuming that geometrically the two tests are similar, it can be accepted that cone resistance, either *qd* (DPT) or *qc* (CPT), are affected for the same soil factors: *texture, density, water content, overburden, OCR… and of course strength of soils.*

In this light - provided that the driving energy of the DPT can be measured and at least a driving formulas (i.e.: Dutch formula) are employed – there would be a one-to-one correlation between DPT and CPT tests as well as a very good agreement of soil strength assessment as shown by [16]–[18].

2. DPT – CPT previous correlation

Given the popularity of SPT and CPT, there have been a large number of researches work in order to express the correlation between SPT blow number (N_{SPT} or precesily $N_{1(60)}$) and CPT cone penetration resistance (*qc*). At present, it is known that the correlation obtained $qc/N_{1(60)}$ is mainly conditioned by the mean grain size of the particles D_{50}.

Concerning previous correlation between dynamic cone tests (DPT) and static cone (CPT) test, litterature and references is less extensive (Table 1). This is mainly because the large amount of DPTs used around the world; where the cone geometry varies and most importantly, the energy transfert ratio (C_E) changes meaningfully for each device. Consequently, significant variability in measurementsare obtained with DPTs and therefore in their correlation with CPT values (see Table 1).

Although at present in Europe ISO 22476-2 standard establishes the different DPTs features – masses, geometry, drive energy… - as well as it is recommended to calibrate the energy transfert ratio (C_E) for all driving system every six months, this is not the case everywhere around the world.

Some studies have shown that it is possible to establish a correlation between DPT and CPT tests [8], [16], [17], [19]–[25]. Generally, good correlations was observed.

However, in order to correlate both tests, it is important to explode the number of blows currently recorded with DPT devices by means of driving formulas such as “the modified Dutch formula”, known also as the “Engineering News formula”:

$$qd = \frac{E}{A*e}\frac{M}{M+M'} \quad (1)$$

With

qd : dynamic cone resistance, expressed in (Mpa)
E : drive energy, currently MgH in (Nm)
g : gravitational acceleration, in (m/s^2)
A : cone section, in (cm^2)
e : permanent settlement or penetration, in mm
M : hammer mass, in (kg)
M’: total driven mass (extension rods, anvil..) in (kg)

Table 1. DPTs and CPT reported previous correlations

Soil type	Correlation	Reference
All soils	$0.3 < q_c/q_d < 1$	(Sanglerat, 1965)
Clay	$q_d \neq q_c$	(Cassan, 1988)
Clayey silt	$q_d = 0.79q_c$	
Clayey sand	$q_d = 0.93q_c+1.88$	
Silty sand and clayey-sandy silts	$q_d = 0.32q_c$	
Sandy silts	$q_d = 0.8q_c$	
Unsaturated sand and gravel	$q_d \neq q_c$	
Saturated sand and gravels	$q_d = 0.4q_c$	
Sand, gravel and clay, above the water table	$q_d/q_c \approx 1$	
Purely cohesive soils : - Above water table - Below water table	 $q_d/q_c \approx 1$ $q_d/q_c > 1$	
Dense and very dense sands and gravels, silty or clayey sands	$0.5 < q_d/q_c < 1$	(Waschkoswki, 1983)
Overconsolidated clays and silts	$1 < q_d/q_c < 2$	
Normally consolidated clays, silts and mud, loose or medium dense sands.	$q_d/q_c \approx 1$	

Early on, (Waschkoswski, 1983)[26], in france recommended the use of the Dutch formula in order to obtain comaprable results and of the same quality with those obtained with CPTs. Recently, J. Powell showed during his intervention at the 19th ICSMGE, that the use of drive formulas for DPTs considerably improves the quality of the data and makes them comparable to those of the CPT [18]. Schnaid et al. [17] implements a driving formula that include, among others, the measurement of driving energy or precesily energy transfert ratio. The approache proposed is appied to SPT and the results are compared with those obtained in-situ by means CPT test. An almost perfect correlation is found for the exposed cases.

Otherwise, another important aspect to consider in order to improve the DPT quality data and consequently their correlation with CPT values, is the variation of the driving energy - or the specific work per blow according to (ISO 22476-2) – according to the hardness of the soil. Indeed, it is known that in the case of heavy (DPH) or super heavy DPSH penetrometers, causes inertial phenomena not considered by driving formulas, understimating thus the cone resistance in, for instance, loose soils ot saturated soft soils.

Consequently, DPT instrumentation, driving energy automatic measurement for each blow as well as the permanent penetration, in addition to use adapted driving formulas (e.g. Dutch formula) and being able to adapt the drive energy to the hardness of soil are thus basic requirements for modern DPT in order to get accurate data and a better correlation with CPT, respectively.

3. The PANDA penetrometer

DPT test is a worldwide practice in geotechnical works and the PANDA dynamic ligyhweight variable energy is, at present, the most developed device. Widely used in France, Europe and other non europeans countries, this penetrometer remains unknown.

Created in 1989 [11], [27], [28], Panda® belongs to the family of dynamic penetrometers whose principle consists in driving a cone fixed to the lower end of a rod into the soil by hammering. The mean idea was to design an instrumented and autonomous measuring dynamic penetrometer, at low cost, that is lightweight and small in size, but with sufficient penetration power to probe most of soils presents in the first ten meters depth. Implementation of variable energy driving, allowing to adapted driving according to the soil compaction encountered during a test, is one of the fundamental principles and the main originality of the device.

3.1. Measuring principle

Panda principle involves penetration of rods into the soil by manual hammering. For each blow, blow energy transmitted is measured at the anvil by strain gauges and other sensors measure the cone penetration. The HMI-box or TDD (from french Terminal De Dialogue), receives both measurements. Dynamic cone resistance *qd* is automatically calculated from modified Dutch formula [8], in which the potential energy is replaced by kinetic energy in Panda 1® [27], [28] and by the elastic strain energy in the second version of the device, the Panda 2 [29]. Difference between two versions concerns the type of measurement, the sensors technology and theoretical background. At the end of the test, measurements are shown on the screen of the HMI-box, thus allowing a graphical representation of *qd* as a function of the depth z.

3.2. Equipment and practical use

Panda® is composed of 6 mains elements: hammer, instrumented anvil, rods, cones, central acquisition unit (UCA) and HMI-box (TDD) (Figure 2.b). The total weight of the device are less than 20Kg, which makes it easily transportable and easy to handle. UCA is an electronic device designed to centralize measurement and recordings made by different sensors. HMI-box (TDD) device allowing communication between the operator and Panda®, in order to define sites and tests, save measurements, visualize surveys, define parameters and device configuration. The instrumented anvil include strain gauges in a "test body" (Figure 2.b) dimensioned in such a way as to obtain a deformation, with each hammer blow, that is as large and reliability without weakening it. Strain gauges are mounted on a Wheatstone bridge. Following the hammer shock, variation in the deformation signal suffered by the test body is transmitted to the UCA for the calculation of the transmitted energy.

Figure 2. (a) General principle of Panda (from french Pénétromètre Autonome Numérique Dynamique Assisté par ordinateur), (b) Panda 2 (2012): main components and (c) examples of Panda® penetrograms obtained in-situ (a very high resolution of sounding log is observed).

In practice, during the test, it is recommended to obtain penetration between 2mm and 20mm per blow, so that the hypotheses of the Dutch formula are verified without significant errors (Zhou, 1997) (Chaigneau, 2001).

This recommendation makes the measurements almost continuous with depth and makes the test a powerful means of identifying the layers thickness. Cone section currently used is respectively 2cm^2 and 4cm^2 and rod diameter is 14mm The first are mainly used for compaction control where depth test are less than 1.50m; while second ones are used for geotechnical investigation, where the test depth is greater and cones overflowing, make it possible to avoid as much as possible the skin friction.

Power of penetration that a man can generate is enough to penetrate soil layers with resistances below 50MPa and for soundings of about 6m deep. Grain size characteristics for which it is limited is (D_{max} < 50mm).

Given the advantages offered by Panda® (variable energy, quality and quantity of measurements, independent of gravity, quick tests, usable on any site, giving access to soil variability estimation...) and because of technological developments made to improve and make reliable, the potential field of application is wide. Panda® is currently mainly used for shallow soil characterization; earthwork compaction control, assessment of the bearing capacity and risk of liquefaction of tailings dams…

3.3. Operation and interpretation

One of the great advantages of the Panda® is that it allows a very fine prospection of layers from very low to high resistance, by controlling the hammering energy, by adapting the hammering intensity. The measurements obtained thus make it possible to establish penetrograms with a very high spatial resolution as illustrated in fig. 2.c. The extensive collection of data provided by the apparatus facilitates the implementation of statistical studies to characterize the mechanical response of the environment and thus study its spatial. Signal processing must be performed on the raw penetrogram in order to filter the signal, especially when using the device in soil investigation. It is common to perform signal clipping (removal of outliers) then smoothing or regularization with a sliding window of constant width Wj (10mm), such that:

$$qd^* = \frac{\sum qd_i \cdot e_i}{\sum e_i} \qquad (2)$$

With qdi the resistance measurements in the window W_j and e_i the measured penetrations.

In addition, since the value measured by Panda corresponds to the net resistance qd, it is advisable, for some calculations, to take into account the influence of the overburden pressure as shown by.

$$qd_1 = qd\left(\frac{p_a}{\sigma'_{vo}}\right)^n \qquad (3)$$

With qd cone resistance (Mpa), p_a atmospheric pressure (1 atm ≈ 103 Kpa ≈ 0,1 Mpa),σ'_{vo} the effective stress of the soil mass and n the stress normalization exponent (0,5).

4. Establishing PANDA- CPT correlation

In this section, it is firstly present laboratory tests carried out to highlight the good agreement between the dynamic and static cone resistance measured by Panda penetrometer. Then, a summary of comparative in-situ tests conducted since 1994 in order to establish empirical correlation between Panda and CPT.

Let us remerber, following comparisons are made for different sites and soil types based on q_d and q_c recorded measurement. These are defined as follow :

- q_d : total dynamic cone resistance computed by Panda penetrometer trough Dutch formula (Equation 1), which is expressed in Mpa.

- q_c : cone resistance measured by CPT (mechanical, electrical or piezôcone). This is computed from the force acting on the cone, Q_c, divided by the projected area of the cone, A_c. This is currently expressed in Mpa. For piezocone systems, q_c is corrected for pore water effects and becomes thus q_t, q_t = q_c + u_2(1- a) [9], [14].

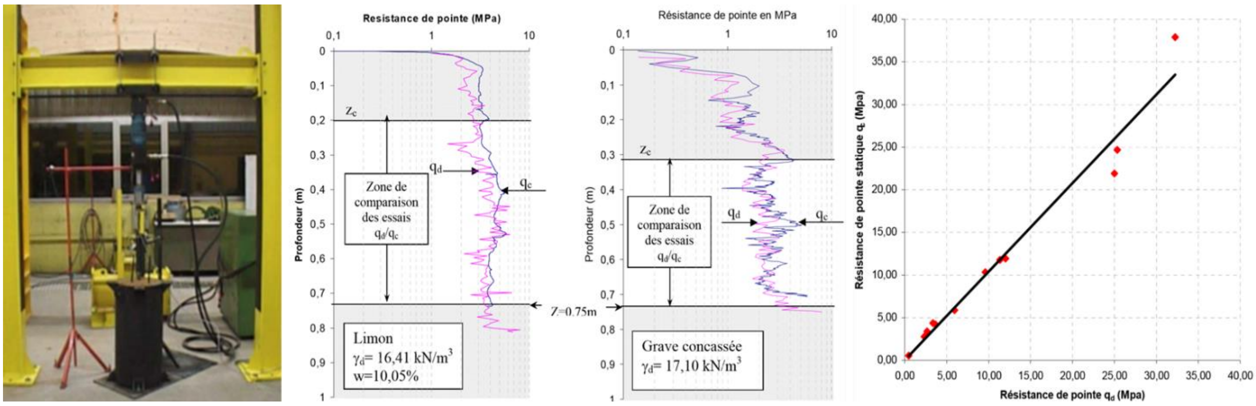

Figure 3. Panda dynamic driving and static sinking (20mm/s) measurements (a) Static sinking test carried out in the calibration chamber (d:400mm/H:800mm) (b) Comparison of dynamic vs static penetrograms for silt and gravel samples, (c) correlation obtained. (from Chaigneau [30])

4.1. Panda dynamic & static measurements

Chaigneau [30] reports experiments carried out in the laboratory whose objective was to compare dynamic cone resistance and those measured, under similar conditions but with a static sinking - such as the CPT (20mm/sec) – on the same device, the Panda. This in order to establish the correlation between both type of measurement. The correlation has been established in a calibration chamber where the nature and condition of the material (compaction and water content) are well controlled (Figure 3). The calibration chamber has a diameter of 38 cm and a height of 80 cm. Boundary conditions are type BC3.

Tree material have been used: silt, sand and gravel. For each of them different samples have been made by varying the water content as well as density. In all, 11 samples were performed, i.e. silt (4), sand (4) and gravel (3). For each sample, two tests were performed through Panda penetrometer: the first by dynamic driving and the second by sinking at a controlled speed of 20 mm/s.

Dynamic driving was carried out according to the mode of operation proper to the Panda test: manual hammering given by a person.

Moreover, static sinking was carried out using a hydraulic press. During the test, displacement was measured with an LDVT sensor and Force with a load cell. Recorded measurements were performed with a 20Hz sample rate. Total tip measured resistance is noted thus q_c. No skin friction was observed during dynamic or static tests. An example of obtained results is presented in (Figure 3.b)

For each sample, the two penetrogram recorded q_d and q_c was smoothed by a sliding window with a step equal to the average penetration. For each tested soil sample, the average resistance values were calculated below the critical depth (200 to 300m) and up to 750 mm deep.

A summary of result obtained by Chaigneau [30] is presented in Table 2. It can be observed from (Figure 3.b) as well as from Table 2 a good agreement between dynamic and static cone resistance measurement. A general correlation for all soil is thus proposed (Figure 3.c).

It can also be observed that the ratio q_d/q_c vary depending to the soil type ($0.75 < q_d/q_c < 0.9$ for silt and $0.85 < q_d/q_c < 1.15$ for sand and gravel) according to the litteratrure values found for classical DPT (Table 1).

Table 2. Summary of Panda dynamic driving vs static sinking performed in laboratory (adapted from Chaigneau [30])

n°	Soil	Density (kg/m^3)	W(%)	qd (MPa)	qc (Mpa)	qd/qc
1	Silt	1.673	10.05	3.69	4.23	0.88
2		1.671	17.48	0.47	0.55	0.86
3		1.729	19.71	3.36	4.35	0.77
4		?	?	2.69	3.39	0.80
5	Sand	1.742	5.18	5.92	5.89	1.01
6		1.751	5.26	11.34	11.79	0.96
7		1.845	4.93	12.02	11.92	1.01
8		1.914	4.19	25.0	21.9	1.14
9	Gravel	1.744	3	2.33	2.78	0.83
10		1.889	3	9.61	10.33	0.94
11		1.941	3	25.32	24.67	1.03

These experiences show that for identical geometric features and for different soils, where conditions was well-controlled, the dynamic cone resistance computed with Panda penetrometer (based on the measurement of the driving energy and the use of the Dutch formula) is comparable to that measured by mean of static sinking (20mm/sec).

Notwithstanding, it must be taken into account that a correlation between Panda and CPT this cannot be established completely in the laboratory through calibration chamber tests (*effects of soil sample fabric, boundary condition, calibration chamber size… on cone penetration resistance measured*).

Indeed, it is also necessary to emphasize that likewise, when comparing the same type of test as the CPT in a homogeneous soil formation, the field q_c measures recorded by two different devices (near each other) can be affected by:

- Type of device: mechanical or electrical cone.
- Dimension and section of used cone.
- Ratio of soil D_{max} and cone diameter used.
- Apex angle of used cone.
- Penetration rate.
- Vicinity of a layer with different characteristics.

These effects have been extensively investigated by a number of different researchers in the CPT's literature.

Consequently, when establishing a field correlation between the Panda (q_d) and CPT (q_c) measurements these effects should not only be taken into account, but also those affecting the Panda dynamic cone resistance (q_d) measurement, such as:

- Skin friction along the rods, and
- Groundwater table

In all of cases, the spatial variability of field soil properties should not be neglected.

In the Table 3, the main characteristics as well as differences between both penetrometer – Panda and classical CPT (ISO 22476-1) – are summarized.

Table 3. Main characteristics and differences between dynamic Panda and classical CPT penetrometers (ISO 22476-1)

Characteristics	Panda	CPT
Cone diameter, D_C (mm)	22	35.3
Cone section, Ac (cm2)	4	10
Cone apex angle, c (°)	90	60
Rod diameter, D_R (mm)	14	35
Ratio D_C/D_R	1.57	≈ 1
Weight rod (kg/ml)	1.17	???
Sinking mode	Dynamic	Constant speed
Penetration rate (mm/sec)	Variable	20
Penetration power capacity, max (kN/m^2)	37000$^{(*)}$	24500
Maximal depth, z_M (meter)	7.0 $^{(**)}$	20-30$^{(**)}$
Device weight (kN)	0.196	24.5
Hammer or truck reaction weight (kN)	0.0173	24.5
Type of measurement (sensor)	Strain gages	Strain gages
Computed parameter (from sensor measurement)	Driving energy	Force
Cone resistance compute	Dutch formula	Force/A_c
Skin friction measurement	Non $^{(***)}$	Yes
Water pressure measurement	Non	Yes

$^{(*)}$ *computed assuming manual hammering, 3mm of penetration per blow, speed of blow 10m/s and an energy ratio C_E of 50%.*

$^{(**)}$ *cunrrent maximal depth of the tests, but it is depend on soil strength as well as equippement.*

$^{(***)}$ *not measure directly, but torque devices measurement can be used in order to asses the skin friction. In most of case, the ratio D_C/D_R is enought to neglect it.*

4.2. Experimental database analysis

A number of studies have been carried out at the Pascal Institute (Clermont Auvergne University) as well as in collaboration with various foreign universities (Escande, 1994) (Zhou, 1997) (Vachon, 1998) (Chaigneau, 2001) (Lepetit, 2002) (Arbaoui, 2003) (l'Excellent, 2004) [28], [30]–[35]. Other comparisons was reported by (Langton, 1999)(Culhaj, 2016)(CRR,2016) [36]–[38] as well as comparative test was facilitated by customers (e.g.: CPTs Australia) .

Indeed, some comparative studies have been carried out in different sites and complete then the experimental database. The sites included:

- Aulnat, in the center of France. Composed by tree layers: clayey sand, clayey silts and marleous clay. 4 CPTu and almost 20 Panda tests were recorded at 4.0 meter depth.
  Gerzat, in the center of France. Composed mainly by clayey silty sands. 5 CPTu and 5 Panda tests was performed at 10m (CPT) and 7m depth (Panda).
- Valparaiso, Chili. In this site, composed mainly by a hydraulic silty sand fill, in all 15 CPTu test and 45 Panda tests was carried out at 6 meter depth.
- Castelo d'empuriés, Girona, Spain. In this site, located in an alluvial plain forming by Mediterranean delta fill, 2 CPTu was reported at 18 meter depth presented by Perez et al. [39]). 8 Panda tests was carried out at 7.0 meter depth.
- Dunkirk, in the North of France. In this site, composed mainly by hydraulic compacted marine shell sand fill, 6 CPTu test was available at 10m and 18m depth. Indeed, 15 Panda tests was performed at 4meter depth.

All of experiences considered in this study are presented in the Table 4. In total, 173 Panda and 93 CPT tests are considered. Various examples of comparatives penetrogram included in this study are also presented in Figure 4, Figure 5 and Figure 6 respectively.

Table 4. Experimental comparative Panda-CPT test considered

Site & Country		Soil	Number of tests		Ref.
			Panda	CPT	
Unspecified	France	Silty clay	1	1	(Escande, 1994)
SFPPT, VNC	USA	Silts, clays and sand	18	18	(Vachon, 1998)
USFD, VNC					
GTL, VNC					
BC, VNC					
Bothkennar	England	Clay, silty sands	1	1	(Langton, 1999)
Cannons Park			1	1	
RAF Cowden			1	1	
Vallabrègues	France	Silts and clays	3	3	(Lepetit, 1999)
Silt (Labs)	France	Silt, sand and gravel	4	4	(Chaigneau, 2002)
Sand (Labs)			4	4	
Gravel (Labs)			3	3	
Sand fill	France	sand	1	1	(Arbaoui, 2003)
Lekaj	Albania	Sand, silt and clays	1	1	(Cullhaj, 2016)
Gjiri I Lalzit			4	2	
Site 0815-19	Australia	Silt and clay	6	6	(CPTs, 2018)
Hydraulic silty sand fill	Chile	Silty sand	45	15	(Villavicencio, 20167
Liège	Belgium	Sand and silts	15	15	(CRR, 2016)
Aulnat	France	Silty sands and clays	20	4	own production
Gerzat	France	Silty sands and clays	15	5	
Dunkirk	France	Marine sand	15	6	
Castelo d'empuries	Spain	Silt, clays and gravels sands	8	2	

Figure 4.a-b present an example od 2/18 comparative tests carried out by Vachon in 1998 [32] at Van Norman Complex in San Fernando Dam (Los Angels, Califronia). Figure 4.c present one of the tree comparative test performed by Lepetit in 1999 [33] at Vallabrègues dams (near to Lyon). In both of exposes cases, A very good agreement – quality and quantity - is observed.

Figure 5.a present the result obtained by Arbaoui in 2003 [34] in a sand pit fill (laboratory). Panda are compared with CPT (gouda cone), and a good correlation is achieved. Figure 5.b-c present 2 of 6 test carried out by CPTs company in Australia. Here sommes quantity differences are observed in a few meters deep.

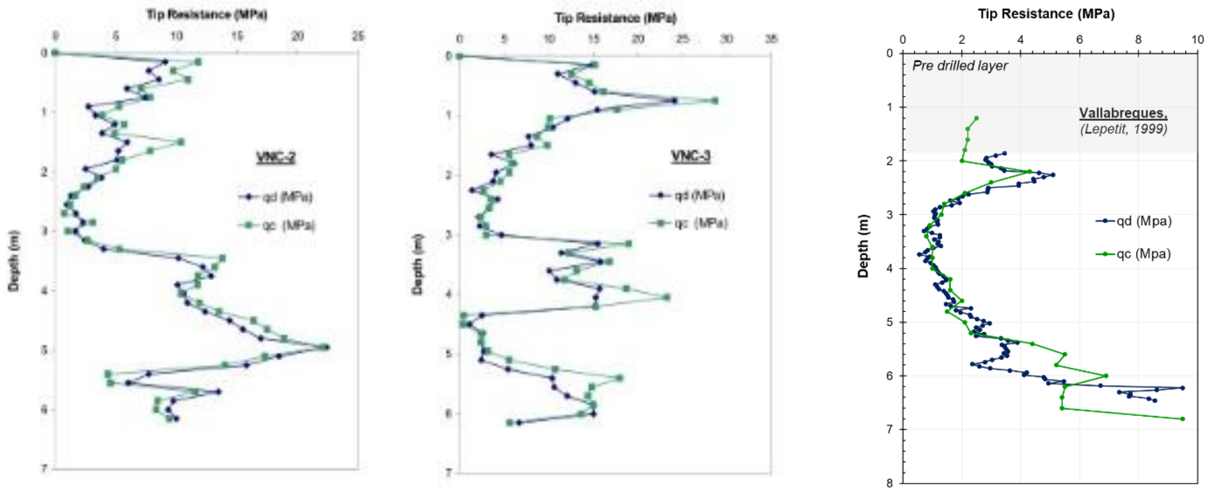

Figure 4. Experimental Panda vs CPT field test. Literature review. (a) and (b) comparative test carried out at Van Norman complex in the San Fernando Dams (Los Angeles, California) (Vachon, 1998) and those performed in France by (Lepetit, 1999) in the Vallabrègues dam.

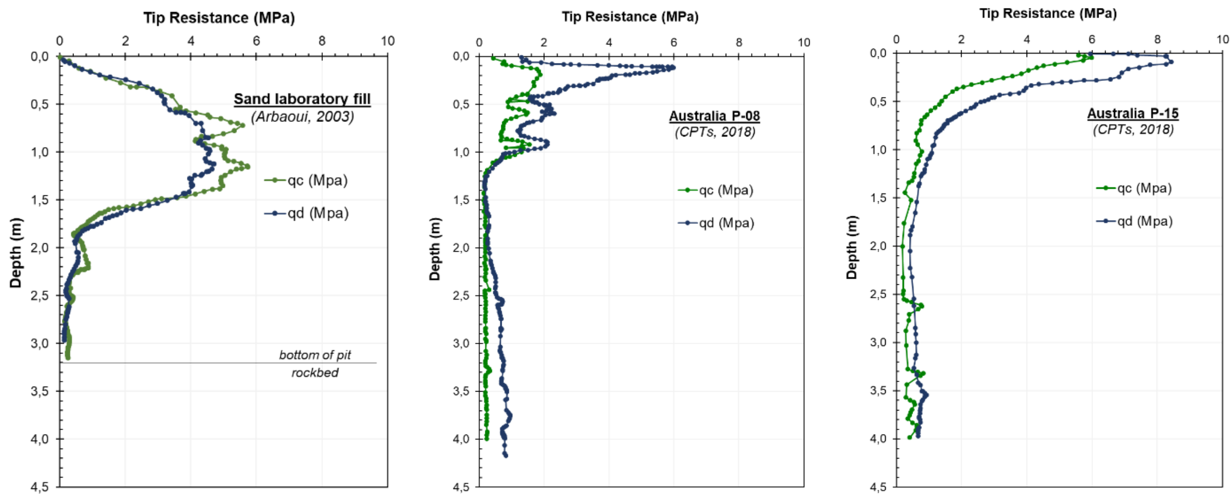

Figure 5. Experimental Panda vs CPT field test. Literature review. (a) test performed in laboratory in a pit sand fill by (Arbaoui, 2003) and (b)-(c) Comparative test carried out in Australia by CPTs company in a silty and clayey soil. Here the signal compared are smoothed every 50mm. (CPTS, 2018).

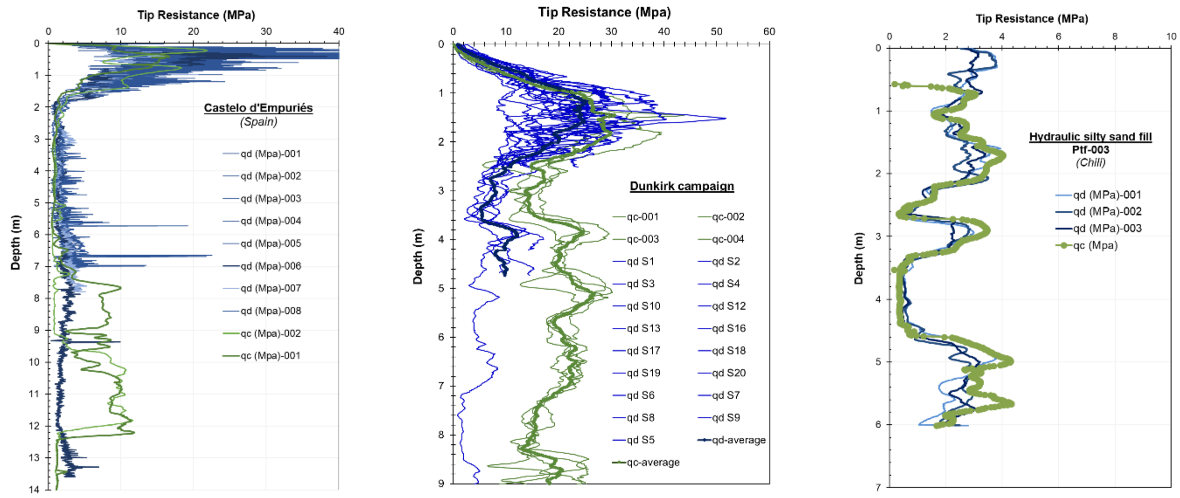

Figure 6. Experimental Panda vs CPT field test performed during this study. Comparatives test carried out in : (a) Castelo d'Empuriés (Spain), (b) Dunkirk (France) marine sand site and (c) Hydraulic silty sand fill in Chile. In all cases the raw data are presented (not smoothed).

In Figure 6 are presented somme examples of comaprative test carried out in this study (Castelo d'empuries, Dunkirk and Chili sites). In spite of the good agreement between the measurement carried out in Spain and Chile, the result obtained at Dunkirk site - marine hydraulic compacted sand- are very different (Figure 6.b) from the other examples. In this case, a good qualitative correspondence in the form of signals is observed.

Nevertheless, a ratio q_c/q_d greater than 3 is obtained lower than 2.5 meter depth, unlike the whole other considered cases. No skin friction was overserved in Panda test and ground water table is noted below 3 meter depth.

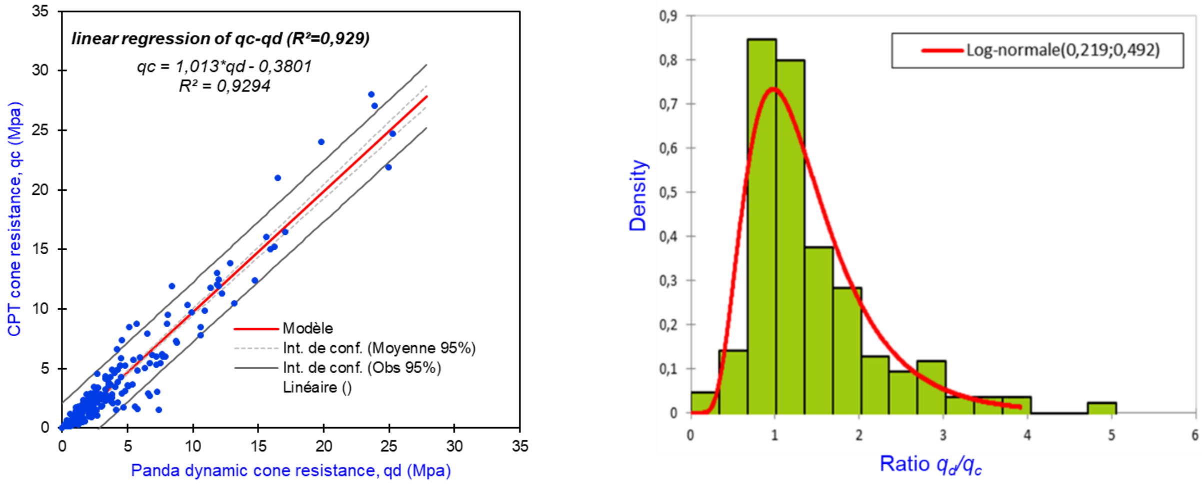

Figure 7. Empirical correlation for Panda & CPT test. (a) 239 pairs of q_d-q_c data extracted from 173 Panda and 93 CPT tests; (b) Histogram of q_d/q_c ratio.

4.3. Panda-CPT empirical correlation

In order to establish the empirical correlation between Panda and CPT test, all raw data collected since the experiences summarized in Table 4 have been digitized. 163 Panda and 93 CPT test are considered.

Each penetrogram is scattered, smoothed and regularized every 200 mm. Once the q_d and q_c signals are processed, for each site and for each couple of comparatives sounding different layers of soil are identified, either by nature or by variability of cone resistance.

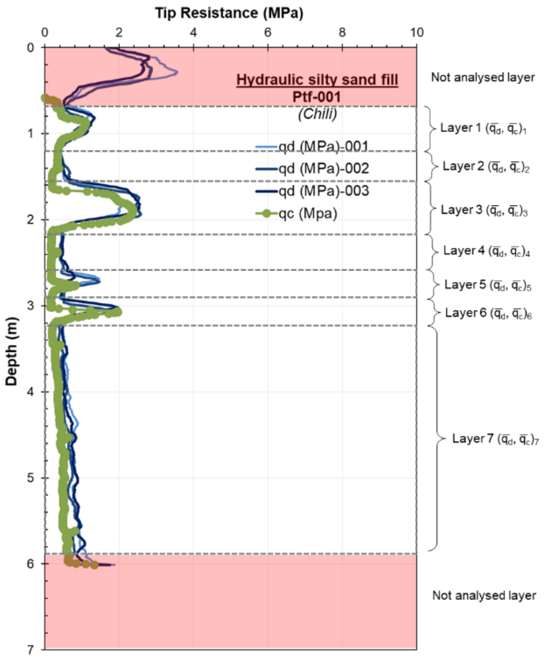

Figure 8. Comparative Panda-CPT tests – Penetrogram processing and analysis performed method. Result obtained in Chile, measurement point Ptf-001.

An example of processing and analysis performed for each penetrogram is presented in the Figure 8. Here, penetrograms obtained are decomposed in 8 layers and average q_d and q_c are computed for each one.

Moreover, in some cases (e;g.: Gerzat, Aulnat, Dunkirk, Chile, Castelo d'empuriés…), 2 or 3 Panda tests have been carried out for each CPT test. These were conducted in the vicinity of considered CPT test. In these cases, the average value of $q_d(z)$ are computed, which was then compared to the $q_c(z)$ recorded signal.

In this way, 239 experimental comparative points are available and the total set of q_d-q_c data are plotted in the graph presented in **Erreur ! Source du renvoi introuvable.**.a. Here, no post-processing data are performed. Indeed, histogram of *qd/qc* is presented in **Erreur ! Source du renvoi introuvable.**.b. Descriptive statistics are summarized in the Table 5.

Table 5. Panda-CPT empirical correlation – descriptive statistics

Variable	Nb	Min	Max	Median	Average	S.D
q_c (Mpa)	239	0.13	28.0	1.96	3.56	4.52
q_d (Mpa)	239	0.19	25.3	2.37	3.89	4.75
q_d/q_c	239	0.56	4.9	1.19	1.43	0.74

Despite the great variability of the data, a very good q_d-q_c correlation is obtained. In the **Erreur ! Source du renvoi introuvable.** the q_d-q_c pairs of data are plotted for different type of soils that was tested.

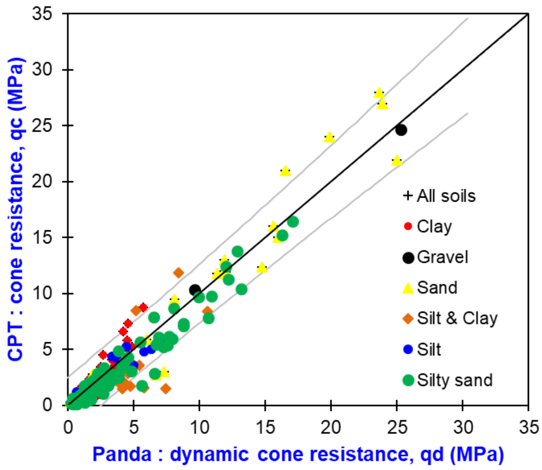

Figure 9. Empirical correlation for Panda & CPT test from 239 pairs of qd-qc data. These have been classified according to soil type.

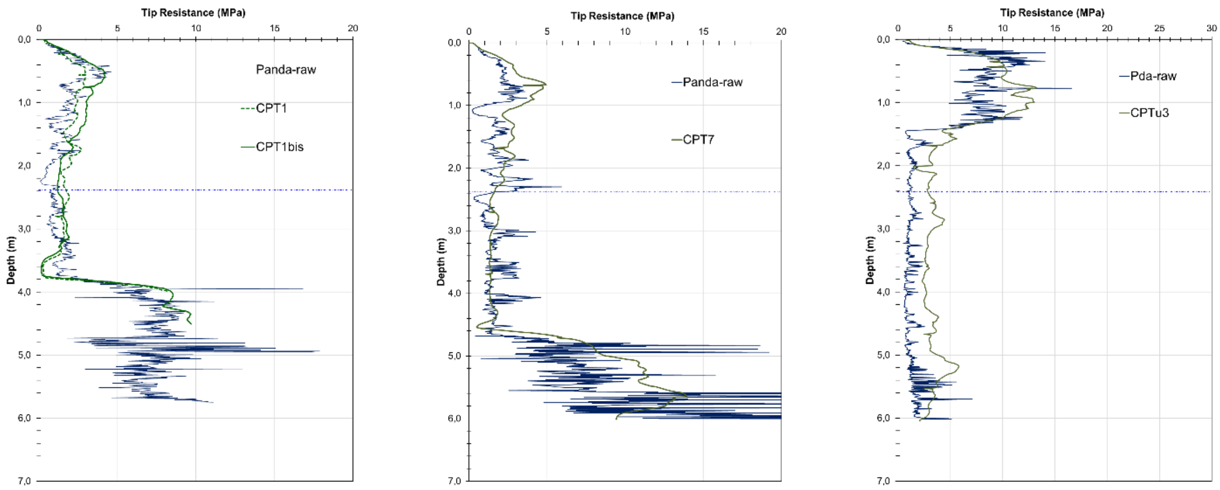

Figure 10. Experimental campaign carried out at Sète Port. 14 Panda test and 14 CPT (9 CPT and 14 CPTu) was performed. In the figure, we present an example of tree comparative test. Raw Panda and CPT penetrogram are presented. (a) point CPT1, (b) point CPT7 and (c) point CPTu3.

The general linear model for q_c predictions from q_d Panda measurement is:

$$q_c = 1.013q_d - 0.38 \quad (4)$$

with R^2=0.93

This model is valid for qd values superiors to 0.4 Mpa.

5. Experimental campaign

In order to show the good correlation between Panda and CPT tests as well as to complete comparative tests, an extensive campaign was carried out recently on a site consisting of marine silty sand embankments.

The site is located in the port of Sète (Hérault, south of France) and it is a land reclaimed from the sea. It was backfilled by dredging sand to a height of between 4 and 7 meters. Groundwater table is found about 2.4 meter depth.

In this site, numerous investigations were carried out in complement to Panda and CPT test, as summarized in Figure 11. These are not presented here.

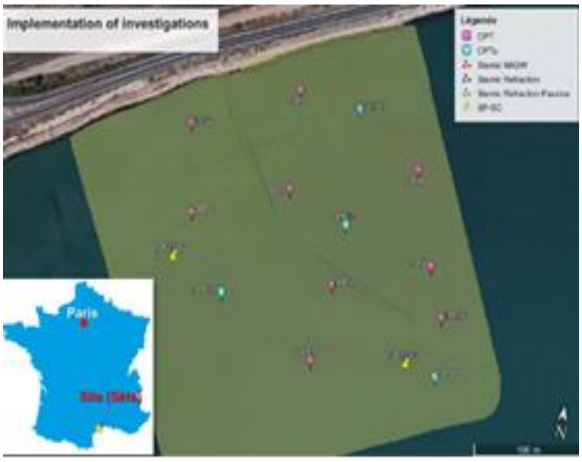

Figure 11. Comparative Panda-CPT tests – Penetrogram processing and analysis performed method. Result obtained in Chile, measurement point Ptf-001.

The following CPT test have been carried out in the Sète site:

- 9 CPT dropped to a depth of 4 to 9 m.
- 4 CPTu conducted to a depth of 9 to 15m.

For each CPT test, one Panda penetrometer was performed. In all, 14 Panda tests was conducted to a depth of 6 meter. For all tests, not skin friction is detected. It has been verified during the accomplishment of each test the absence of torque. This was measured with a digital torque de-vice every 1 meter depth.

In the Figure 10, 3 of 14 comparative test are presented. The penetrogram presented correspond to the raw data. As has been shown in most of test presented here, a good agreement can be observed between the results obtained from Panda and CPT. However, in 1 of the 14 comparative test (Figure 10.b), it has been observed a q_c/q_d ratio > 2.5 such as Dunkirk test presented below (Figure 6.b).

From whole graphs presented as well as results obtained, it is possible to identify four main layers constituting the embankment (6 to 7 meters height):

- 1st medium compaction layer (0-1.40m),
- 2nd very loose sandy layer (1.40 to 3.80m/4.6m)
- 3rd transition compact sand layer (3.8m/4.6m to 6 m)
- The bottom layer (z > 6.0 m).

For each pair of comparative tests, and for each identified layer, the averages values of q_d and q_c was computed according to the procedure show in Figure 8 below. The descriptive statistics of q_d-q_c analysis data obtained at Sète port are presented in the Table 6.

Table 6. Experimental campaign at Sète port – descriptive statistics

Variable	Nb	Min	Max	Median	Average	S.D
q_c (Mpa)	30	1.13	8.04	2.05	3.23	2.10
q_d (Mpa)	30	1.23	9.63	3.39	4.35	2.52
q_d/q_c	30	0.38	1.14	0.76	0.74	0.19

The obtained model to predict q_c values from q_d Panda measurement here is:

$$q_c = 1.12q_d + 0.72 \quad (5)$$

with R^2=0.88

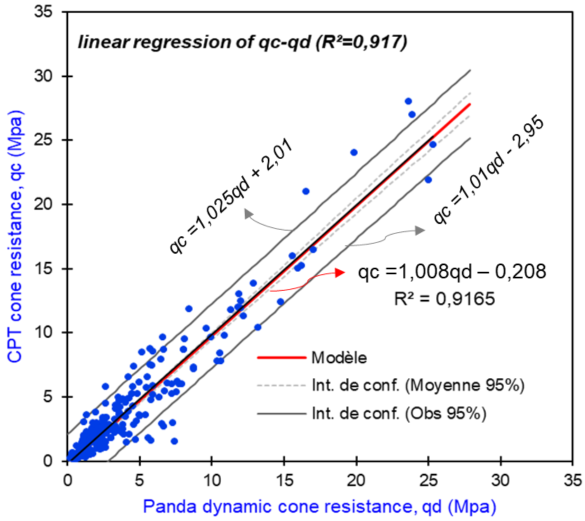

Figure 12. Empirical relationship for Panda & CPT test based on a simple linear model regression and valid for all soil.

Considering all data presented here, a general correlation is then proposed (Equation 6) and presented in the (Figure 12).

A general and simple empirical relationship between Panda and CPT test valid for all soils is thus proposed:

$$\begin{aligned} &\text{Average} \quad q_c = 1.008q_d - 0.21 \\ &\text{Min} \quad q_c = 1.007q_d - 2.95 \\ &\text{Max} \quad q_c = 1.025q_d + 2.01 \end{aligned} \tag{6}$$

These models are valid for q_d values greater than 0.4Mpa and less than 50 Mpa. In addition, these models should be considered reliable as long as the skin friction along the rods is neglected.

Finally, in general cases, it can be written that:

$$0.87 < q_c/q_d < 1.11 \tag{7}$$

6. Conclusions

In this article, an experimental study was presented in order to establish an empirical correlation between Panda lightweight dynamic penetrometer and Cone penetrometer CPT.

After introducing the development of penetrometer test in geotechnical practice, the Panda equipment has been presented. This is the most developed dynamic penetrometer and three important concepts are introduced by this device :

- driving energy measurement by strain gages,
- adaptative drive energy (hand hammering), and
- use of Dutch formula to compute qd.

These aspects make the measured dynamic cone resistance signal - penetrogram - qualitatively and quantitatively comparable to those obtained with more developed equipment such as the CPT.

In addition, dynamic penetrometer Panda® is a practical, quick and efficient method for shallow soil characterization. The repeatability, reliability and sensibility of the results make it an appropriate in-situ tool for assessing spatial variability of soil mechanical parameters, even in areas difficult access.

In order to improve the interpretation of dynamic resistance qd measured with Panda, an empirical correlation with static cone resistance qc measured with CPTs devices was studied.

After compiling and digitizing most of studies reported and where comparative Panda-CPT test have been conducted, a simple correlation analysis (linear correlation) has been performed. To the bibliographic data were added those recently made by ourselves.

In all, 187 Panda and 107 CPT test have been analyzed. It has been found, in most cases, a very good correlation between the two test.

A linear model to predict *qc* values from measurements of *qd* made with Panda is proposed. This model is reliable if skin friction along the rods is not detected during the test.

While the proposed model is simple and reliable, it needs to be improved, specially ion order to introduce the nature of soil, or e;g.: size grain distribution characteristics D_{50}, to improve qc predictions.

Finally, the main purpose of this study is not to confront Panda and CPT methods, but to bring them together and thus provide a quick and easy method to optimize shallow geotechnical campaign by coupling Panda and CPT. This will reduce ignorance about spatial variability of soils and reduce the risk associated.

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