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Correlation between static (CPT) and dynamic variable energy (P.A.N.D.A.) cone penetration tests

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ABSTRACT: Dynamic penetrometer is a worldwide practice in geotechnical exploration and French lightweight dynamic penetrometer, P.A.N.D.A., is the most developed device nowadays. Widely used in France, in Europe and other countries, its remains however unknown. This paper presents the P.A.N.D.A. test and the main goal is to establish an empirical correlation with the CPT test. This study is based on about 100 comparative tests performed the last 20 years. 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 qd-qc correlation is proposed.

Keywords: In-situ test, Penetrometer, Correlation, P.A.N.D.A., DPT, CPT.

1. Cone penetration testing

Among the wide range of in situ 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 17th 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 20th 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" (fig. 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] developed 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 developed 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)[9]. 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 forty years [10], [11]; 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 [12] developed the first instrumented dynamic variable energy penetrometer: the P.A.N.D.A.® (fig 1.b-c). A general description of this device, 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 assess the strength resistance of soils by pushing a cone into the soil was developed early, between 1920-1950, and it was initially P. Barentsen in 1930 who invented the Dutch cone penetrometer [13]. Since 1950 the developments 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 accelerometers, inclinometers, visiocameras, geophones…

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

Unlike DPT test, a large number of references are available describing technical, practical and technological topics of CPT as well as interpretation and geotechnical analyze of the results obtained (i.e.:[10], [14]).

In Europe, both electrical or piezocone CPT test, are referenced by the standard (ISO 22476-1). Indeed, currently feedback of experiences (in-situ or laboratory), test databases as well as literature references allows to evaluate state, stress-strain parameters of soils from *qc* value are large and exhaustive [10], [14]–[16].

Undoubtedly cone penetration tests, dynamic (DPT) or static (CPT), are a worldwide used tool for soil characterization. Notwithstanding its geometrical similarities, the main difference 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, which makes it difficult its analysis.

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 both 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 light of this (and 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 relationship between DPT and CPT tests as well as a very good agreement of soil strength assessment as shown by [17]–[19].

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 precisely $N_{1(60)}$) 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 soil particles D_{50}.

Concerning previous correlation between dynamic cone tests (DPT) and static cone (CPT) test, literature and references is less extensive (Table 1). This is mainly because for the large type of DPTs used around the world; the cone shape change and most importantly, the energy transfer ratio (C_E) varies for each device. Although at present in Europe ISO 22476-2 standard establishes the different DPTs features (masses, geometry, drive energy…) and recommends to measure the energy transfer ratio (C_E) for all driving system every six months, but it is not systematically applied.

Consequently, significant variability in measurements is obtained with DPTs and therefore in their correlation with CPT values (see Table 1). However, some studies have shown that it is possible to establish a relationship between DPT and CPT tests and generally, good correlations were observed [8], [17], [18], [20]–[26].

In order to correlate both tests, it is important to analyze the number of blows currently recorded with DPT devices by means of driving formulas such as “the modified Dutch formula”:

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

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 penetration, in (mm)
M: Mass of hammer, in (kg)
M’: total driven mass (extension rods, anvil...) in (kg)

Early on, (Waschkoswski, 1983)[27], in France recommended the use of the Dutch formula in order to obtain reliable and comparable results with those obtained with CPTs. Recently, J. Powell showed (during his intervention at the 19th ICSMGE) that the use of drive formulas for DPTs, improves considerably the quality of the data and makes them comparable to those of the CPT [19].

Schnaid et al. [18] implements a driving formula that include the drive energy or precisely energy transfer ratio measurements. The proposed approach is applied 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.

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.	$q_d/q_c \approx 1$	

Otherwise, another important aspect to improve the quality of DPTs data, and consequently their correlation with CPT values, is the possibility to change the drive energy (or the specific work per blow according to (ISO 22476-2)) along the test according to the soil's hardness. Indeed, it is known that in the case of heavy (DPH) or super heavy DPSH penetrometers, causes inertial phenomena not considered by driving formulas, underestimating thus the cone resistance in, for instance, loose soils or saturated soft soils.

Consequently, the device instrumentation, the measurement of driving energy and permanent penetration per blow, the use of an adapted drive formulas as well as the possibility to change the drive energy during the test are some basic requirements for the modern dynamic penetrometer test.

3. The P.A.N.D.A. [28]

The P.A.N.D.A. (from French *Pénétromètre Autonome Numérique Dynamique Assisté par ordinateur*) is a dynamic lightweight variable energy penetrometer. Widely used in France, in Europe and other non-Europeans countries, this penetrometer remains unknown. At present, P.A.N.D.A. is the most developed DPT.

Created in 1989 [12], [28], [29], the mean idea was to design an instrumented and autonomous measuring dynamic penetrometer, low cost, lightweight and small in size, but with sufficient penetration power to probe most of soils presents in the first 10-meters depth. The implementation of variable drive energy, that allows to adjust the penetration power according to the soil compaction is one of the fundamental principles and the main originality of this dynamic penetrometer.

3.1. Measure principle

P.A.N.D.A. principle involves penetration of rods into the soil by manual hammering. For each blow, the drive energy is measured at the anvil by strain gauges. Other sensors measure the permanent cone penetration. The HMI dispositive, 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 the elastic strain energy [30]. At the end of the test, measurements are shown on the screen of the TDD, thus allowing a graphical representation of qd as a function of the depth z.

3.2. Equipment and practical use

Basically, P.A.N.D.A. is composed of 6 elements: hammer, instrumented anvil, rods, cones, central acquisition unit (UCA) and TDD (fig. 2.b). The total weight is 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. The TDD allows the communication between the operator and P.A.N.D.A. in order to program the sites and the tests as well as to save measurements, visualize the performed surveys… The instrumented anvil include strain gauges (fig. 2.b) mounted on a Wheatstone bridge. Following the hammer blow, variations in the strain signal suffered by the anvil are transmitted to the UCA and drive energy is then calculated. 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 is 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.

Moreover, 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 important errors. This makes the measurements almost continuous with the depth and makes the P.A.N.D.A. test a powerful means to identify the layer thickness.

The power penetration that a man can generate is enough to penetrate soil having resistances below 50MPa as well as to down the test until 6meter depth.

Given the advantages offered by P.A.N.D.A. (*variable energy, quality and quantity of measurements, independent of gravity, quickness of the test...*) the potential field of application is wide. P.A.N.D.A. is mainly used for shallow soil characterization; compaction control of earthworks, assessment of the bearing capacity…

3.1. Operation and interpretation

One of the great advantages of the P.A.N.D.A. test is that it allows a very fine prospection either for very low to high resistance soils, by adapting the hammering energy and intensity of blow. Measurements obtained thus make it possible to establish penetrograms (*plot of cone dynamic resistance qd vs depth z*) having a high resolution as illustrated in figure 2.c. The extensive collection of data provided facilitates the implementation of statistical analysis in order to characterize the spatial variability of soils [31], [32].

In light of this, signal processing must be performed on the raw penetrogram in order to filter the signal, especially when using the device in soil investigation.

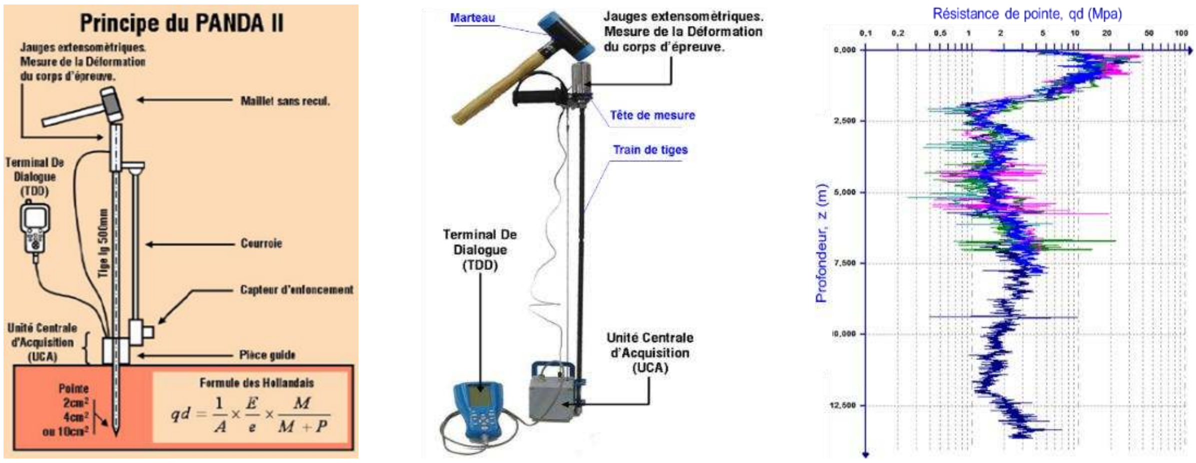

Figure 2. (a) General principle of P.A.N.D.A. (from french Pénétromètre Autonome Numérique Dynamique Assisté par ordinateur), (b) P.A.N.D.A. 2 (2012): main components and (c) examples of P.A.N.D.A. penetrograms obtained in-situ.

It is common to perform a signal clipping (removal of outliers) then a signal smoothing by mean of a sliding window of constant width Wj (10mm):

$$qd^* = \frac{\sum qd_i \cdot e_i}{\sum e_i} \tag{2}$$

With qd_i the cone dynamic resistance measured into the window W_j and e_i is the measured penetration.

In addition, since the value measured by P.A.N.D.A. 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 (Liao and Withman, 1986; Olsen and Mitchell, 1994).

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

With qd cone dynamic 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 assumed equal to 0,5 for sandy soils.

4. P.A.N.D.A.- CPT relationship

In this section, it is firstly presented the laboratory tests carried out to highlight the good agreement between dynamic and static cone resistance measurement performed by mean of P.A.N.D.A. Then, a summary of in-situ comparative tests that were carried out since 1994 is presented in order to establish empirical relationship between P.A.N.D.A. and CPT tests.

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

- q_d: dynamic cone resistance computed by P.A.N.D.A. penetrometer through the Dutch formula (equation 1), which is expressed in Mpa.
- q_c: cone resistance measured by CPT (mechanical, electrical or piezocone). 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, $q_t = q_c + u_2(1 - a)$ [10], [15].

4.1. Dynamic & static measurements

Chaigneau [33] reports experiences carried out in laboratory whose main goal were to compare dynamic cone resistance and static penetration (20mm/sec) measured on the same device, the P.A.N.D.A. The correlation has been established in a calibration chamber having a diameter of 38 cm and a height of 80 cm (fig. 3).

Three materials 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 prepared: silt (4), sand (4) and gravel (3). On each sample, two tests were performed, the first by dynamic driving and the second by mean of a controlled speed penetration (20 mm/s).

Dynamic driving was carried out manually and at variable drive energy and static penetration was carried out using a hydraulic press. Here, during the test, the cone displacement was measured with an LVDT sensor and force was measured 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 (fig. 3.b).

For each sample, both penetrograms recorded, q_d and q_c, were smoothed and the averages resistances values were calculated below the critical depth (200 to 300m) and up to 750 mm deep.

A summary of result obtained is presented in the Table 2. A good agreement between dynamic and static cone resistance measurements can be observed from the figure 3.b) as well as from the Table 2 and a general correlation for all soil is thus proposed (fig. 3.c).

It can be also observed that the ratio q_d/q_c varies according to the type of soil: $0.75 < q_d/q_c < 0.9$ for silt and $0.85 < q_d/q_c < 1.15$ for sand and gravel samples. This are within the range of values indicated in the literature for classical DPT (Table 1).

These experiences show that for identical geometric features and for different soils, where conditions were well-controlled, the dynamic cone resistance computed with P.A.N.D.A. is comparable to that measured by mean of static sinking (20mm/sec).

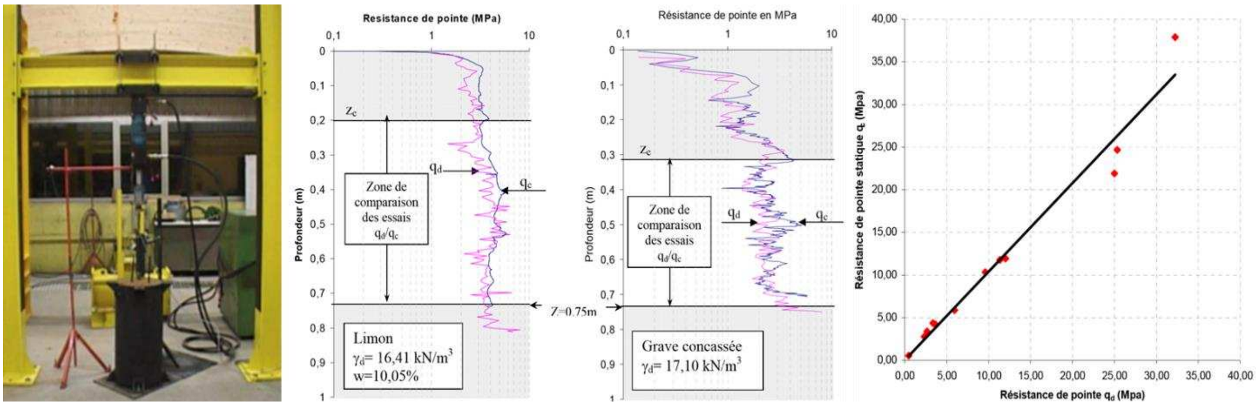

Figure 3. P.A.N.D.A. dynamic and static penetration (20mm/s) measurements (a) Static penetration test carried out in a calibration chamber (d:400mm/H:800mm) (b) Comparison of dynamic vs static penetrograms for silt and gravel samples, (c) qd-qc relationship (from Chaigneau [33])

Notwithstanding, a correlation between P.A.N.D.A. and CPT tests 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*).

Table 2. Summary of P.A.N.D.A. dynamic vs static penetration performed in laboratory (adapted from Chaigneau [33])

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

Indeed, when comparing the same type of test as the CPT in a homogeneous soil, field q_c measurement made by two different devices (near each other) can be affected by [8], [34], [35]:

- Type of cone: mechanical or electrical cone [36], [37].
- Dimension, section and surface roughness of cone and sleeve.
- Apex angle of used cone [38], [39].
- Load cell design and calibration.
- Ratio of soil D_{max} and cone diameter used.
- Penetration rate [40], [41].
- Vicinity of a layer with different characteristics (thickness, density, texture...) [42]

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

- Skin friction along the rods, and
- Groundwater table (below or above

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

In the Table 3, the main features of P.A.N.D.A. and CPT test are summarized presented.

Table 3. Main characteristics of P.A.N.D.A. and classical CPT penetrometers (ISO 22476-1)

Characteristics	P.A.N.D.A.	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)	12000$^{(*)}$	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, penetration per blow of 3mm, speed of blow 10m/s and an energy ratio C_E of 50%.*

4.2. Experimental database analysis

In order to propose à simple and general relationship between P.A.N.D.A and CPT tests, in this section, a hundred comparative test were carried out in-situ are analyzed

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) [29], [33], [43]–[47].

Other comparisons test was reported by (Langton, 1999)(Culhaj, 2016)(CRR,2016) [48]–[50], and other experiences were facilitated by customers.

To complete the experimental database, during this study some comparative tests have been also carried out in different sites:

- Aulnat (center of France). Composed by three layers: clayey sand, clayey silts and marleous clay. In this site, 4 CPTu and almost 20 P.A.N.D.A. tests were recorded at 4-meter depth.

- Gerzat (center of France). Composed mainly by clayey silty sands. Here, 5 CPTu and 5 P.A.N.D.A. tests were performed at 10m (CPT) and 7m depth (P.A.N.D.A.).
- Valparaiso (Chili). In this site, composed mainly by a hydraulic silty sand fill, in all 15 CPTu test and 45 P.A.N.D.A. tests were carried out at 6-meter depth.
- Castelo d'Empuriés (Girona, Spain). Located in an alluvial plain forming by Mediterranean delta fill, in this site 2 CPTu were reported at 18 meter [51]). 8 P.A.N.D.A. tests were carried out at 7-meter depth.
- Dunkirk (North of France). Composed mainly by hydraulic compacted marine shell sand, here, 6 CPTu tests were carried out at 10m and 18m depth and 15 P.A.N.D.A. tests were performed at 4meter depth.

All of experiences considered are summarized in the Table 4 where soil type is also indicated. In all, 163 P.A.N.D.A. and 93 CPT tests are considered. Examples of comparatives penetrogram included in this study are also presented in the figure 4 to figure 6.

Table 4. Experimental comparative P.A.N.D.A.-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	

In the figure 4.a-b, it is present 2 of 18 comparative tests were carried out by Vachon in 1998 [44] at Van Norman Complex in San Fernando Dam (Los Angeles, California). The figure 4.c present 1 of 3 comparatives test performed by Lepetit in 1999 [45] at Vallabrègues dams (near to Lyon). In both presented cases, a very good agreement – quality and quantity - is observed between qd and qc values.

Furthermore, in the figure 5.a the results obtained by Arbaoui in 2003 [46] are presented. Here, P.A.N.D.A. was compared with CPT (Gouda cone) in a laboratory sand pit fill. A very good match is achieved.

In the figure 5.b-c, 2 of 6 test carried out by CPTs company in Australia are presented. In this case, although the general shape of the signals match well, differences are observed between qd and qc magnitudes. For the P-15 tests (fig. 5.c), this difference is constant for the whole depth, while for test P-08 (fig. 5.b), a great difference is observed at the first 0,5m depth as well as from 2m depth. Here, further 2m depth, the qd-qc difference increases proportionally with depth, which may be caused by skin friction along the rods for P.A.N.D.A. test.

In the figure 6 several examples of comparative test performed in this study (Castelo d'Empuries, Dunkirk and Chili sites) are presented. In spite of the good agreement between the measurements that were carried out in Spain and Chile, the result obtained at Dunkirk site, in France, are very different from the other examples (fig. 6.b). Notwithstanding the good correspondence between the shape of signals obtained (the *qd* and *qc* penetrogram match well), there are a wide difference in the magnitude of qd and qc values obtained. In fact, unlike the other presented cases, here a ratio of q_c/q_d greater than 3 is obtained lower than 2.5-meter depth.

During the P.A.N.D.A test, no skin friction was observed, which allows to rule out that this is the main cause. Regarding the water table and the effects that the overpressure generated during penetrometer driving may have on the results obtained, it should be noted that the hammering was carried out (further 2m depth), with a very low driving energy in order to reduce the overpressure of water generated by blow and minimize then the effects on qd measurements.

In addition, this difference can also be related to the measurement of the CPTu. It is known that the use of cones having load cells to measure high strength soils lose reliability in soft soils [52]… as it is the case of Dunkirk site (see fig. 6.b). Some other factors which may have disturbed the CPT's measures are those listed above (§4.1). The difference founded here, can be maybe also caused by the nature of soil (sand shell), it what crushed during dynamic penetration, modified then its strength or drainage characteristics.

Nevertheless, it is not enough to explain the great difference between qd and qc resistance observed here. A more detailed analysis is needed in order to clarify it.

4.3. P.A.N.D.A. and CPT empirical correlation

To establish an empirical correlation between P.A.N.D.A. and CPT test, all raw data collected since the experiences summarized in the Table 4 have been considered 163 P.A.N.D.A. and 93 CPT tests.

All raw penetrograms were 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 test, different layers of soil were identified, either by nature or by cone resistance changes in depth.

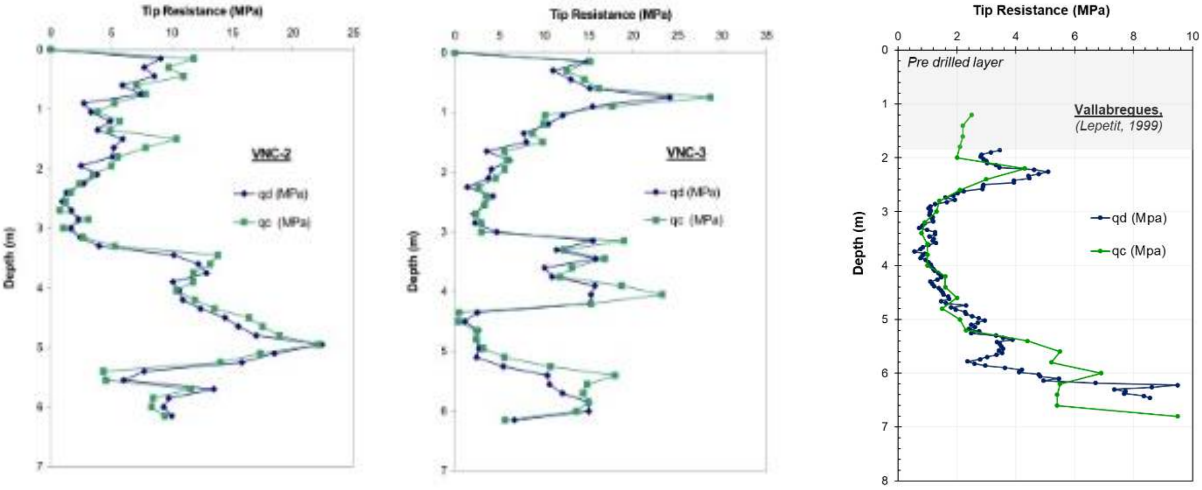

Figure 4. Experimental P.A.N.D.A. vs CPT field test. Literature review. (a) and (b) comparative test carried out at Van Norman complex in the San Fernando Dams (Los Angeles, California) (Vachon, 1998) and those performed in France by (Lepetit, 1999) in the Vallabrègues dam.

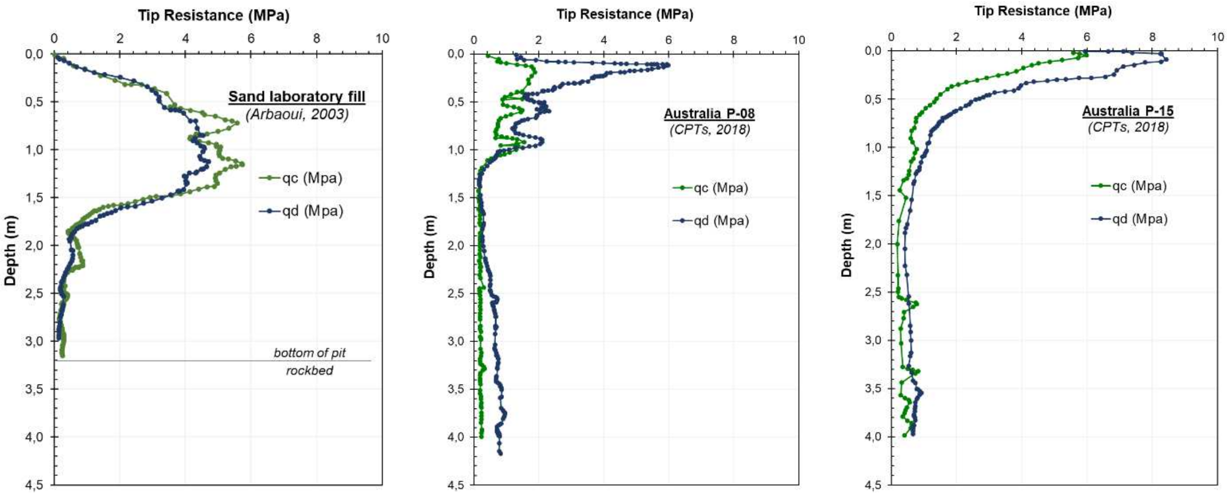

Figure 5. Experimental P.A.N.D.A. vs CPT field test. Literature review. (a) test performed in laboratory in a pit sand fill by (Arbaoui, 2003) and (b)-(c) Comparative test carried out in Australia by CPTs company in a silty and clayey soil. Here the signal compared are smoothed every 50mm. (CPTS, 2018).

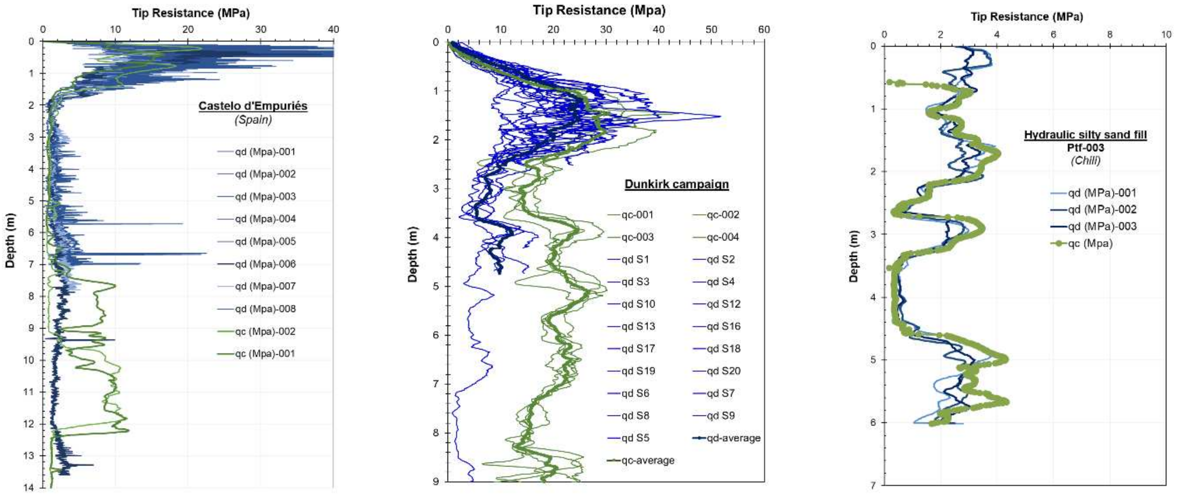

Figure 6. Experimental P.A.N.D.A. vs CPT field test performed during this study. Comparatives test carried out in: (a) Castelo d'Empuriés (Spain), (b) Dunkirk (France) marine sand site and (c) Hydraulic silty sand fill in Chile. In all cases the raw data are presented (not smoothed).

An example of processing and analysis performed for each penetrogram is presented in the figure 8. Here, penetrograms obtained in Valparaiso (Chili) 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 P.A.N.D.A. tests have been carried out for each CPT test. These were conducted in the vicinity of each CPT test. In these cases, the average value of $q_d(z)$ are computed, which was then compared to the measured $q_c(z)$ values.

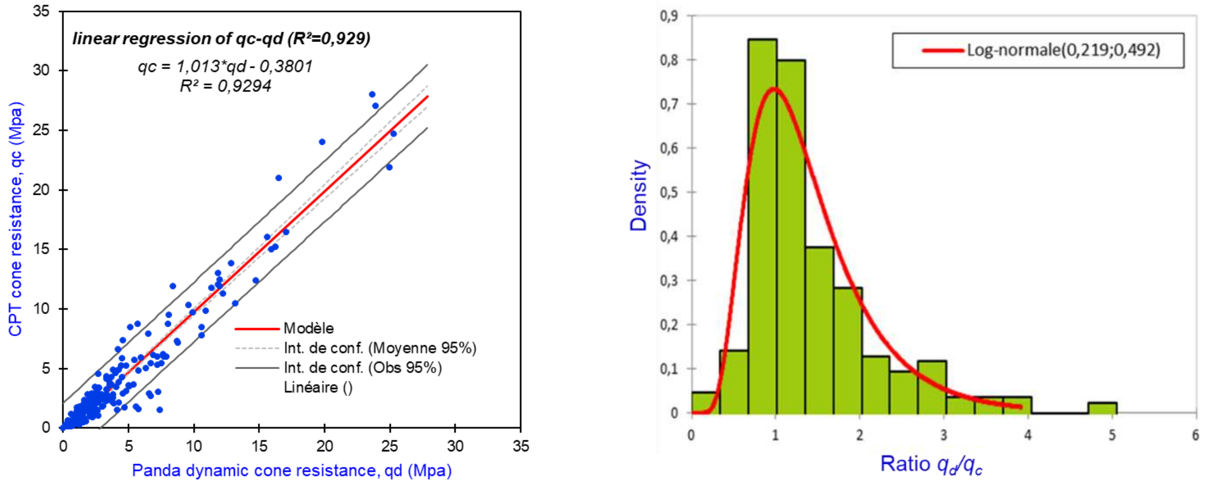

Figure 7. Empirical correlation for P.A.N.D.A. & CPT test. (a) 239 pairs of q_d-q_c data extracted from 173 P.A.N.D.A. and 93 CPT tests; (b) Histogram of q_d/q_c ratio.

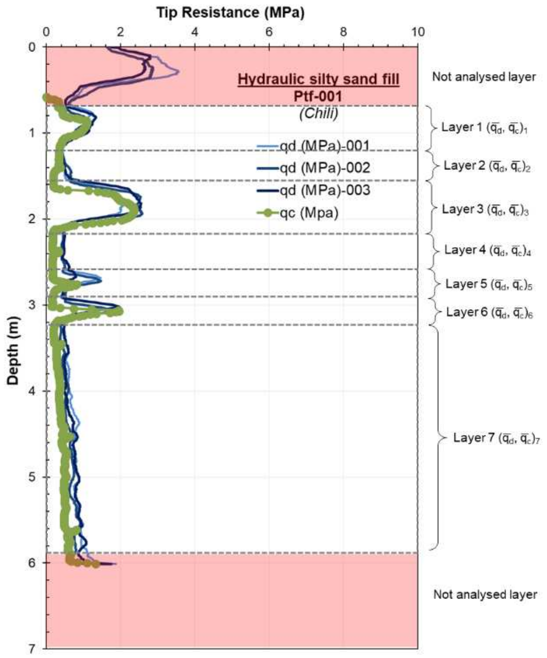

Figure 8. Comparative P.A.N.D.A.-CPT tests – Penetrogram processing and analysis performed method. Result obtained in Chile, measurement point Ptf-001.

Table 5. Descriptive statistics of P.A.N.D.A. and CPT tests empirical correlation

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

It can be note, and despite the great variability of the data obtained, a good relationship between *qd* and *qc* values. In this way, the general linear model for static resistance q_c predictions from dynamic resistance q_d obtained with P.A.N.D.A. penetrometer is:

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

with R^2=0.93

This model is reliable for qd values greater than 0.40 MPa.

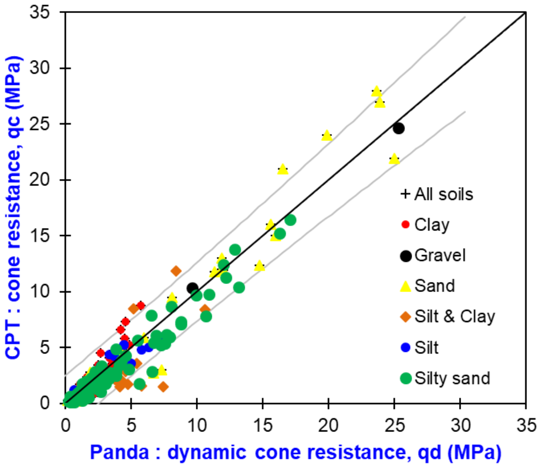

Figure 9. Empirical correlation for P.A.N.D.A. & CPT test from 239 pairs of qd-qc data for different soil class.

5. Experimental campaign

In order to show the good correlation between both tests as well as to complete comparative database, 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. The total height of the embankment is between 4 and 7 meters and water table was founded at about 2.4-meter depth.

As presented in the figure 11 in this site, numerous investigations were carried out in complement to P.A.N.D.A. and CPT tests.

- 9 CPT were downed to a depth of 4 to 9-meter.
- 4 CPTu were conducted in between 9 to 15-meter.
- 14 P.A.N.D.A. were conducted to 6-meter. For all tests, not skin friction was measured along the rods. It has been verified (every 1-meter depth) during each test by mean of torque measurements.

In the figure 10, 3 of 14 raw comparative test are presented. As has been shown in most of test presented here, a good agreement is found between static and dynamic cone resistance measurements. However, in 1 of the 14 comparative test (fig. 10.b), it has been observed a q_c/q_d ratio > 2.5 such as Dunkirk test presented previously.

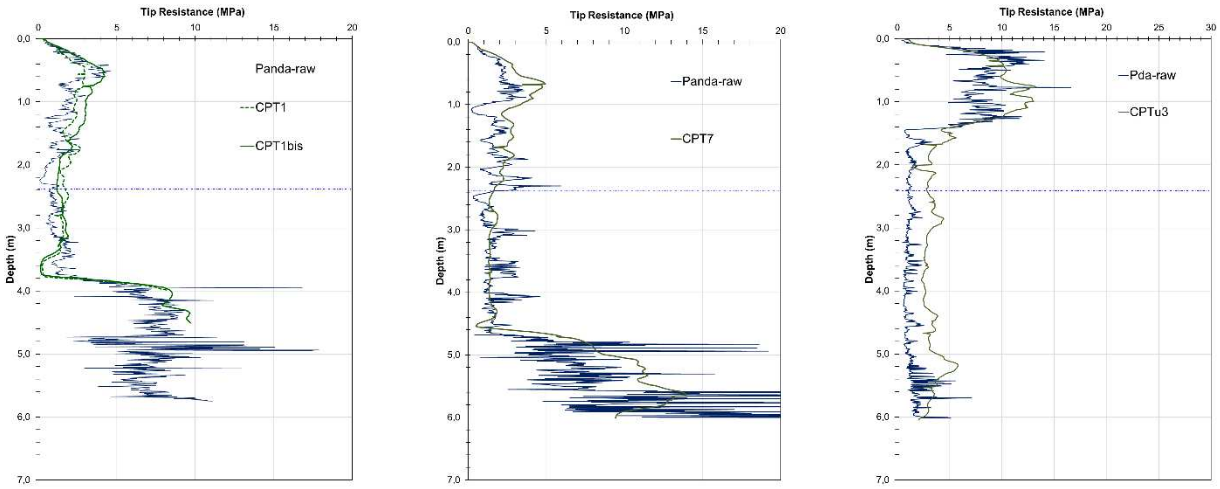

Figure 10. Experimental campaign carried out at Sète Port. 14 P.A.N.D.A. test and 14 CPT were performed. In the figure, an example of three raw comparative test are presented. (a) point CPT1, (b) point CPT7 and (c) point CPTu3.

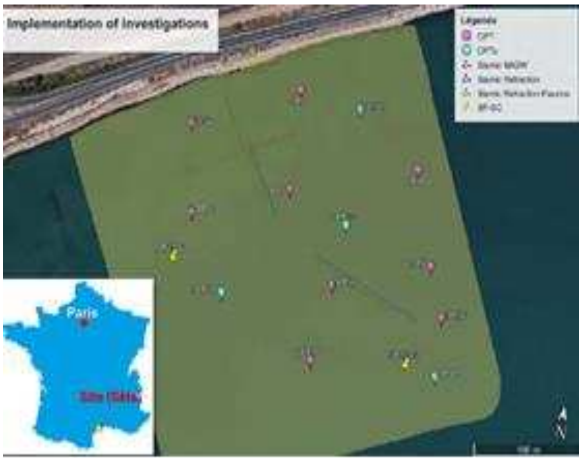

Figure 11. Experimental campaign, Sète Port, France.

In this way, 239 experimental comparative points are obtained. The dynamic cone resistance q_d of P.A.N.D.A. are plotted against static cone resistance q_c values in the graph presented in the figure 7.a in where any post-processing analysis were performed. In the figure 9, the values of qd vs qc are plotted according to the nature of soil. Nevertheless, in the further *qd-qc* relationship analysis this is not considered mainly because not much data are available for some class of soils.

In addition, the histogram of the ratio *qd/qc* is presented in the figure 7.b and descriptive statistics analysis are summarized in the Table 5.

It is possible to identify from whole graphs presented four main layers constituting the embankment:

- 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 couple of comparative tests, and for each identified layer, the averages values of q_d and q_c were computed (according to the procedure show in the figure 8). The descriptive statistics of q_d-q_c analysis data obtained at Sète port site 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

Here, the obtained model to predict static resistance q_c values from dynamic cone resistance q_d values obtained with P.A.N.D.A. is:

$$q_c = 1.12q_d + 0.72 \tag{5}$$

with R^2=0.88

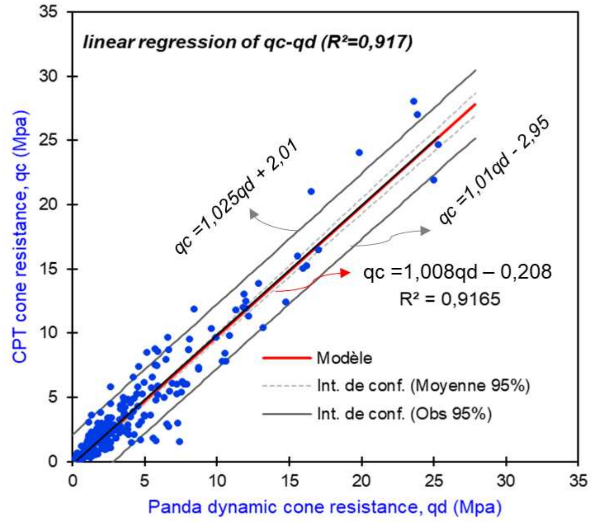

Figure 12. Empirical relationship for P.A.N.D.A. & CPT test based on a simple linear model regression and valid for all soil.

Considering now all data presented here, a general simple and lineal correlation is then proposed (equation 6) and presented in the (fig. 12).

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

These models are reliable for q_d values greater than 0.4Mpa and less than 40 Mpa. In addition, these models should be considered reliable as long as the skin friction along the rods is neglected. Finally, in most of cases it can be written that:

$$0.85 < q_c/q_d < 1.15 \qquad (7)$$

Where qc is the static cone resistance measured with CPT and qd is the dynamic cone resistance obtained with P.A.N.D.A. and computed by mean of the Dutch formula.

6. Conclusions

In this article, an experimental study was presented. The main goal was to establish an empirical correlation between dynamic P.A.N.D.A. lightweight penetrometer and static cone penetrometer CPT.

After introduce the development of penetrometer test in geotechnical practice, the P.A.N.D.A. equipment has been presented. Currently, this is the most developed dynamic penetrometer and three important concepts are introduced:

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

These aspects make the computed dynamic cone resistance signal - penetrogram - qualitatively and quantitatively comparable to those obtained with the CPT test. In addition, 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 area difficult to access.

In order to improve the interpretation of dynamic resistance qd measured with P.A.N.D.A., an empirical correlation with static cone resistance qc was studied.

After collecting most of studies reported in different sources, a simple correlation analysis (linear correlation) has been performed. In all, 177 P.A.N.D.A. and 107 CPT test have been analyzed. It has been found, in most cases, a good correlation between the two penetration test.

In this way, a linear model to predict static cone resistance *qc* values from dynamic cone resistance *qd* measurement performed with P.A.N.D.A. 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 in order to include the nature of soil, or most precisely the grain size distribution characteristics D_{50}, density, water content…

Finally, it must be point out that the main purpose of this study is not to confront P.A.N.D.A. and CPT methods, but to bring them together and thus provide a quick and easy method to optimize shallow geotechnical campaign by coupling both methods or provide an economical alternative to CPT test. This will reduce ignorance about spatial variability of soils and reduce the risk associated.

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