The PANDA®, Variable Energy Lightweight Dynamic Cone Penetrometer : A quick state of art

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Abstract. Dynamic penetrometer is a worldwide practice in geotechnical works and Panda® lightweight variable energy is the most developed device at present. Widely used in France, Europe and many other countries, Panda® remains unknown. In this article we present a quick state of the art of this technique. The principle, the use and interpretation as well different relationship with other methods and geotechnical parameters are here exposed.

Keywords. Panda, Dynamic penetrometer, soil characterization, in-situ test, compaction control, soil correlation

1. Introduction

Dynamic penetration tests (DPT) are a worldwide technique for soil characterization. Due to its rapid implementation, affordability and suitability for a large range of soils, DPT are present in many countries. This 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 [2]. Goldmann described a dynamic penetrometer 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 also took place in Germany with the development of a lightweight dynamic penetrometer, the *Künzel Prüfstab* [4], later taken over by [5] and standardized in 1964 as the "Light Penetrometer Method" (fig. 1.a).

With the European development of DPTs and because of its simplicity, many developments have taken place throughout the world. Scala [8] developped in Australia the Scala dynamic penetrometer, which has been widely used for design and control of pavement [9] [10] [11] [12]. Sowers and Hedges [13] developed the Sowers penetrometer, for in-situ soil exploration and to assess the bearing capacity of shallow footings.

Webster et al. [14] and the US Army Corps of Engineers developed the dual mass DCP, well known in North America (ASTM 6951). The Mackintosh probe has developed recently by Sabtan and Shehata [15].

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Figure 1. (a) Prüfstab Künzel-Paproth" [6] (b) Panda® lightweight dynamic variable energy penetrometer: first generation [7] and (c) Panda 2®: second generation.

Low driving energy and limited probing depth caused the development of heavier devices in Europe and USA (*SPT, Borros…*). Several generations of DPTs have followed one another and we can find today a wide variety of them [15] and their use and features are described by ISO 22476-2. Nevertheless, despite the wide variety of DPTs developed the last century, the mean principle, the equipment and technology no changes and remains the same as that described by Goldmann in 1699 and the *Künzel Prüfstab*. In fact, in contrast to the CPT, which has undergone significant technological development [20] [21] [22], DPTs stayed away from these advances and remain old and rudimentary.

It was only at the end of the 1980s that the first major improvements took place. In France, Roland Gourvès developed the first instrumented lightweight dynamic variable energy penetrometer: The Panda® (fig. 1.b).

2. The PANDA® penetrometer

Created in 1989, the mean idea was to design an instrumented and autonomous measuring dynamic system, at low cost, that is lightweight, but with sufficient penetration power to probe most of shallows soils. Variable energy driving, allowing to adapted driving according to the soil compaction encountered during a test, is the main originality of the device [23] [24] [25]. Currently, two version of Panda® have been developed and a third is being prepared.

2.1. Measuring principle, equipment & practical use

Panda® principle is that of DPTs. Nevertheless, for each blow the energy is measured at the anvil by means of strain gauges. Other sensors measure cone penetration per blow. The HMI, named TDD, receives both measurements and dynamic cone resistance *qd* is automatically calculated by modified Dutch formula [19]; where potential energy is replaced by kinetic energy in the first version [28] and by the elastic strain energy in the second version [27] of Panda®.

The device is composed by 6 main 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.

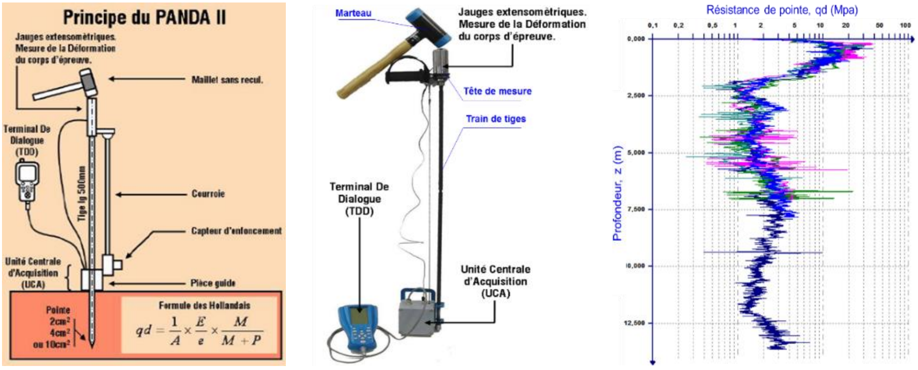

Figure 2. (a) General principle of Panda® (from french Pénétromètre Autonome Numérique Dynamique Assisté par ordinateur), (b) Panda 2® set (2012): main components and (c) examples of Panda® penetrograms obtained in-situ (a very high resolution of sounding logs can be observed).

The UCA is an electronic device designed to control the measurements and recordings made by the different Panda's sensors. The TDD is a PDA interface (HMI) and facilitates communication between the operator and Panda®, site edition, test programming and their visualization at the end. The instrumented anvil includes strain gauges and immediately after one blow, deformation signal is transmitted to the UCA, as well as penetration per blow. Cone resistance *qd* is calculated and recorded immediately.

In practice, it is recommended to obtain penetration per blow from 2 to 20mm along the test [28] [40]. In this way, measurements are almost continuous with depth and makes the test a powerful means of identifying the thickness of layers or pathogenic sections in depth (Fig. 3.c). Used rod diameter and length is 14mm and 500mm, while cone section commonly employed is respectively 2cm^2 (surface compaction control) and 4cm^2 (deep soil characterization). Penetration power that a man can generate is enough to penetrate soil layers having cone resistances below 50MPa and the total sounding depth can reach 6 meter. About soil characteristic, grain size is limited to D_{max} < 50mm. Panda® is currently used for soil shallow characterization; compaction control of earthworks, railways control, assessment of the bearing capacity, liquefaction risk evaluation…

3. Processing, interpretation and explode

One of the great advantages of the Panda® is that it allows a very fine sounding of soil layers having very low to very high cone resistance. The main result, the penetrogram, provide a very high spatial resolution signal in depth (fig. 2.c). In addition, the ease of repeating field test, facilitates the implementation of statistical analyzes that allow characterizing the soil mechanical response and establish their spatial variability[40] [36] [41] [42] [43] [44]. However, in most cases, signal processing must be performed on raw penetrograms, especially when analyzing deep soil investigation tests. In this way, it is common to make a signal clipping (outliers remove), then a smoothing and/or a regularization with a sliding windows of constant width W_j (10mm).

$$qd^* = \frac{\sum qd_i \cdot e_i}{\sum e_i} \quad (1)$$

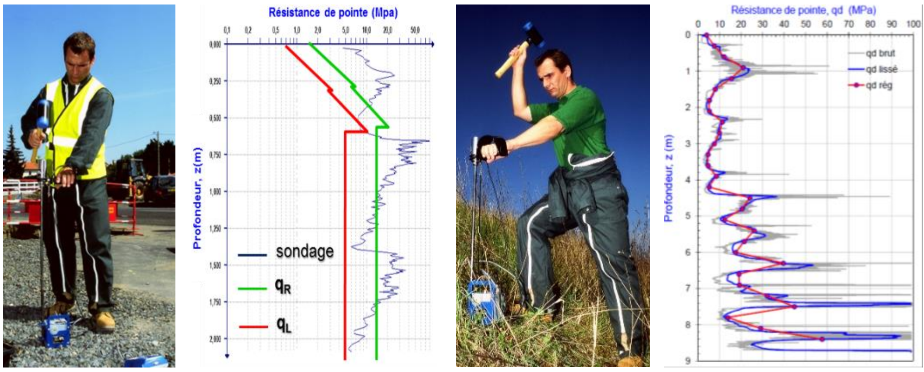

Figure 3. (a) **Panda**® test for earthwork compaction control and (b) Fundamental principle of interpretation, (c) geotechnical investigation tests and (d) raw, smoothed and regulated Panda® penetrograms.

Where qd_i and e_i are respectively the cone resistance and blow penetration measured into the window W_j. Moreover, since measurements of *qd* correspond to the net cone resistance, it is recommended, for calculations purposes, to consider the overburden pressure effects [45] [46] [47] [48].

$$qd_1 = qd\left(\frac{p_a}{\sigma'_{vo}}\right)^n \quad (2)$$

Where *qd* is the raw or smoothing cone resistance, p_a is atmospheric pressure (1atm ≈ 0,1 Mpa), σ'_{vo} is effective stress and *n* a normalization exponent (often take as 0,5).

3.1. Compaction control, density and bearing capacity (CBR) estimation

Compaction control by using dynamic penetrometer has been developed over the last thirty years and is described by French standard (NF 94-105). It consists to compare the penetrogram obtained with two references curves respectively, q_R and q_L. These curves, determined usually in the laboratory by calibration for different materials, compaction degrees and water content, are included in a database [26] [40] [49]. In fact, univocally relationship between con resistance, dry density and water content has been shown [28] [40]. The general established model is as shown in (Eq. 3) where A, B and C are the regression coefficient determined for each soil and included in the database. Recently, [50] considered saturation degree (*Sr*) in order to improve sand density prediction (Eq. 4). If soil and water content are unknown, it can be considered the (Eq.5). Bulk density (Eq. 6) can be also estimated with a good agreement for all soils.

$$\gamma_d = A(w) + B\ln(qd) + C \quad (3)$$

Relative density (D.R) can be also approach with Panda®. [51] establish, for silty sands and mine waste rock, a correlation between (*D.R*) and qd_1. (Eq. 7). Moreover, for normally consolidated sands it can be considered (Eq. 8) and in all cases it can be accepted (Eq. 9):

California bearing ration CBR. Several studies have established a correlation (figure 5.a) between the Panda® test and the CBR value determined according to the recommendations of ASTM 6951 (Eq. 10).

Table 1. Density and compaction control using Panda® - Synthesis of correlation.

<table>
<tr><th>Soil parameter</th><th>Expression</th><th colspan="4"></th><th>equation</th></tr>
<tr><td rowspan="4">Dry density</td><td rowspan="4">$\gamma_d = Aln(Sr) + Bln(qd) + C$</td><td>Soil type</td><td>A</td><td>B</td><td>C</td><td rowspan="4">(eq. 4)</td></tr>
<tr><td>gravels & sands</td><td>1.88</td><td>0.73</td><td>18.49</td></tr>
<tr><td>sandy soils</td><td>2.48</td><td>0.47</td><td>18.53</td></tr>
<tr><td>Clay and silts</td><td>3.20</td><td>0.84</td><td>17.25</td></tr>
<tr><td>Dry density</td><td>$\gamma_d = 1{,}06 \cdot ln(qd) + 15{,}82$</td><td colspan="4">All soils</td><td>(eq. 5)</td></tr>
<tr><td>Bulk density</td><td>$\gamma_T/\gamma_w = 0{,}36 \cdot log\left(\frac{qd}{p_a}\right) + 1{,}43$</td><td colspan="4">All soils. (adapted from CPT test)</td><td>(eq. 6)</td></tr>
<tr><td rowspan="3">Relative Density</td><td>$D.R = 28{,}5 \cdot \ln\left(\frac{qd_1}{pa}\right) - 65{,}40$</td><td colspan="4">silty sands and mine waste rock</td><td>(eq. 7)</td></tr>
<tr><td>$D.R = 100 \cdot \sqrt{\frac{qd_1}{300 \cdot pa}}$</td><td colspan="4">normally consolidated sands</td><td>(eq. 8)</td></tr>
<tr><td>$D.R = 4{,}22 \cdot \sqrt{\frac{qd_1}{pa}} + 17{,}71$</td><td colspan="4">All sandy soils</td><td>(eq. 9)</td></tr>
<tr><td rowspan="4">CBR (%)</td><td rowspan="4">$CBR = \alpha \cdot (qd)^{\beta}$</td><td colspan="2">Soil type</td><td>α</td><td>β</td><td rowspan="4">(eq. 10)</td></tr>
<tr><td colspan="2">All soils</td><td>1.56</td><td>1.10</td></tr>
<tr><td colspan="2">Plastic clays and silts</td><td>3.27</td><td>1.00</td></tr>
<tr><td colspan="2">Clays and silts of low plasticity (CBR< 10)</td><td>0.304</td><td>2.00</td></tr>
</table>

(*) pa atmospheric pressure 1atm = 0.103Mpa

3.2. Correlation with other geotechnical tests

Several works have been carried out to correlated the cone resistance qd of Panda® and other geotechnical tests (*CPT, SPT, PMT...*) (Table 2).

Correlation with SPT (N_{60} - qd). Considering great similarity of the tests and despite the high variability of the results obtained with the SPT probe, it has been demonstrated that there is a good relationship between the cone resistance *qd* and N_{SPT} or N_{60} blows number. This depends mainly on the grain size distribution of the soil (Eq. 11-12).

Correlation with the CPT (qc - qd). When drive energy is controlled and adapted, it has been found that dynamic resistance qd have a good correspondence with net resistance qc of CPT. Different studies have shown that there is a very good correlation between Panda® and CPT. In most cases it can be considered qd qc (Eq 13-14)

Correlation with the PMT (pl - qd, EM - qd). Although the pressuremeter is most widely test used in France, very few comparative studies with dynamic penetrometer Panda® was carried out. Nevertheless, several correlations between the cone resistance *qd* of Panda® and Ménard pressuremeter results (p_L and E_M) for different soils are presented and can be considered (Eq. 15)

Correlation with the DCP (IDCP - qd). Widely known in America (ASTM 6951) and throughout the world, DCP is close to Panda®. Given its similarity, it has been shown that there is a very good correlation between cone resistance qd and penetration index IDCP of DCP. It is depended on weight hammer of DCP (Eq. 16).

Table 2. Soil characterization by using Panda® - Synthesis of regression coefficients.

Geotechnical test	Expression				equation
Standard penetration test SPT	$\frac{\left(qd/pa\right)}{N_{60}} = \alpha$	Soil type	α		(eq. 11)
		Organic clays	*1,8 à 2,4*		
		Clays	*2,2 à 3,0*		
		Silt, clayey silts and silt mixtures	*2,8 à 3,6*		
		Silty and clay sand	*3,0 à 4,5*		
		Sands	*4,4 à 6,8*		
	$\frac{\left(qd/pa\right)}{N_{60}} = A \cdot {D_{50}}^{B}$		*A*	*B*	(eq. 12)
		All soil	*5.44 - 6.64*	*0.2 - 0.28*	
Cone penetration test CPT	$qc \cong (0{,}93 \text{ à } 1{,}05) \cdot qd$	*All granular and cohesive soils normally consolidate*			(eq. 13)
	$qc = 0{,}94 \cdot qd + 0{,}39$				(eq. 14)
Pressuremeter test PMTt	$\left(qd/p_L\right) \approx \alpha_{pl}$	*Soil type*	α_{pl}	β_{EM}	(eq. 15)
		clays	*2,2 à 4,0*	*3,0 à 5,7*	
	$\left(E_M/qd\right) \approx \alpha_{E_M}$	*silts*	*2,8 à 5,6*	*2,0 à 4,2*	
		sands	*7,2 à 9,4*	*0,9 à 1,8*	
Dynamic cone probing DCP (ASTM 6951)	$qd = \alpha IDCP^{-1} + \beta$	*DCP hammer*	*α*	*β*	(eq. 16)
		4.7kg weight	*62.4*	*0.37*	
		8.0kg weight	*108.7*	*0.27*	
		All cases	*97.8*	*0.31*	

3.3. Soil characterization parameters

Panda ® is a very interesting and powerful tool to characterize shallow soils. Several works have been carried out in order to correlate cone resistance and some geomechanical parameters of soils (Table 3).

Estimation of friction angle. For sands and sandy mixtures, friction angle can be estimated using (Eq. 17-18). Recently, [57] [69] [70] propose some relationships to relate friction angle, cohesion, cone resistance qd Panda® and saturation degree for fine soils

Estimation of undrained shear strength (s_u-qd). Classically, it is assumed that the undrained shear strength on fine soils is very good correlated with the dynamic cone resistance *qd* of dynamic penetrometer. (Eq. 19) can be used with Panda® cone resistance in fines soils.

Estimation of the shear wave velocity (Vs-qd). In general, a good estimation of shear wave velocity can be obtained from cone resistance qd and (Eq. 20-21). In addition, by knowing the shear wave propagation rate and dry density (Eq. 4-5), the shear modulus G (Mpa) can be determined (Eq. 22) with a good agreement.

Estimation of the deformability modulus (E-qd). Elastic modulus can be approached using penetration cone resistance qd (Eq. 23); particularly odometer modulus (E_{oed}). Linear relationship has been proposed in literature between q_d and E_{oed} for different soils (Eq. 24) and a good estimation can be found.

Table 3. Soil characterization by using Panda® - Synthesis of correlations.

<table>
<tr><th>Soil parameter</th><th>Expression</th><th colspan="2"></th><th>equation</th></tr>
<tr><td rowspan="2">friction angle (ϕ')</td><td>$\phi' = 14{,}4 + 5{,}61 \cdot \ln({qd_1}/{pa})$</td><td colspan="2" rowspan="2">For sands and sandy mixtures</td><td>(eq. 17)</td></tr>
<tr><td>$\phi' = 17.2 \cdot ({qd_1}/{pa})^{0.185}$</td><td>(eq. 18)</td></tr>
<tr><td rowspan="5">undrained shear strength (s_u)</td><td rowspan="5">$s_u = \frac{qd - \sigma_{vo}}{N_{kt}}$
Where $N_{KT} \approx 0.285*IP + 7.64$</td><td>$N_{KT}$(*)</td><td>IP range</td><td rowspan="5">(eq. 19)</td></tr>
<tr><td>11</td><td>10 to 12</td></tr>
<tr><td>13</td><td>12 to 25</td></tr>
<tr><td>17</td><td>25 to 40</td></tr>
<tr><td>23</td><td>> 40</td></tr>
<tr><td rowspan="2">shear wave velocity (Vs)</td><td>$\log Vs = (0.12 \cdot \gamma_T + 0{,}194 \log z)$</td><td colspan="2">Adapted from CPT literature</td><td>(eq. 20)</td></tr>
<tr><td>$Vs = 78{,}15 \cdot qd^{0{,}39}$</td><td colspan="2">All soils</td><td>(eq. 21)</td></tr>
<tr><td>Shear modulus (G)</td><td>$G = V_s^2 \cdot \gamma_d$</td><td colspan="2"></td><td>(eq. 22)</td></tr>
<tr><td>Elastic Young's Modulus (E)</td><td>$E = 2 \cdot (1 + \mu) \cdot G$</td><td colspan="2"></td><td>(eq. 23)</td></tr>
<tr><td rowspan="8">Oedometric modulus (E_{OED})</td><td rowspan="8">$E_{oed} \approx \alpha \cdot qd$</td><td>Soil type</td><td>α</td><td rowspan="8">(eq. 24)</td></tr>
<tr><td>Compact clays</td><td>3.0 - 5.0</td></tr>
<tr><td>Soft clays (qd <1.0Mpa)</td><td>5.0 - 9.5</td></tr>
<tr><td>Sandy clays</td><td>2.8 - 3.6</td></tr>
<tr><td>Clayey silts</td><td>2.5 - 4.0</td></tr>
<tr><td>Silt, sandy silt</td><td>1.0 - 2.0</td></tr>
<tr><td>Clayey sands, silty sands</td><td>2.0 - 5.0</td></tr>
<tr><td>Sands</td><td>1.0 - 2.0</td></tr>
</table>

3.4. Other cases studies

Panda® is used to evaluate bearing capacity of shallow foundation, to improve slopes soil characterization as well as to assess the liquefaction risk of tailings dams. earthwork compaction control, transport and railways structures sounding…

Shallows foundations: ultimate and admissible bearing capacity. dynamic penetrometer is an efficient and reliable tool to assess the admissible and ultimate bearing capacity according to ELU and ELS. Formulas commonly used:

$$Q_{adm-ELU} \approx \frac{qd}{5 \text{ à } 7} \qquad\qquad Q_{adm-ELS} \approx \frac{qd}{14 \text{ à } 20} \tag{25}$$

Precise evaluations of bearing capacity or settlement of shallow foundation can be made through the theory of bearing capacity (Terzaghi, 1943; Meyerhof, 1956; Brinch Hansen, 1968; Boussinesq; Magnan et al, 2014) and considering soil nature (cohesive or non-cohesive) as well as different soil parameters estimated from Panda® (Sanglerat, 1972; Fabian, 2002; Sanhueza and Villavicencio, 2010).

Determination of liquefaction risk. A realistic model of soil behaviour and liquefaction risk requires a fine detailed characterization as well as vertical evolution of the physical, mechanical and dynamic properties of soils. From in-situ test, the main objective is to assess the variation of cyclic resistance ratio (CRR) considering an earthquake whit magnitude (M_w: 7.5). Based on the (Seed and Idriss, 1971; Robertson and Wride, 1997; Robertson and Fear, 1998, Robertson, 2009) works (Lepetit, 2002) propose a method to assess liquefaction potential with Panda®. Here the main parameters of Robertson's method are substituted by cone resistance qd and soil permeability coefficient k (Duchesne et al. 2004).

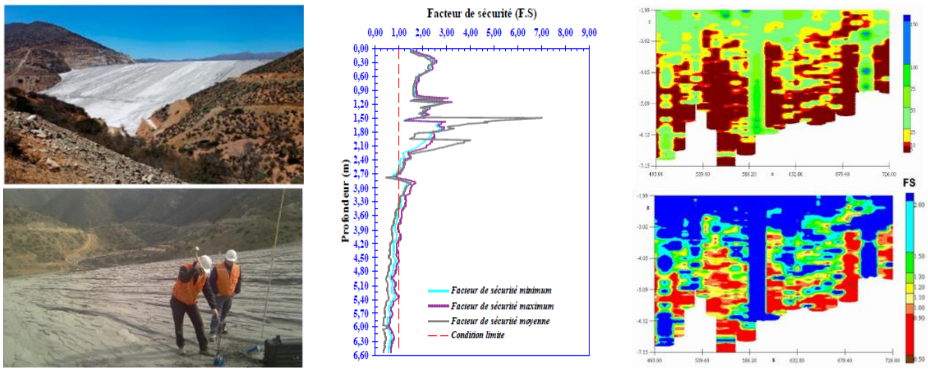

Figure 4. Panda® surveys conducted for compaction control and liquefaction risk assessment of Tailings dams (c.f. Espinace et al. 2013), (b) Evolution of the safety factor for deep liquefaction from qd_{N1cs} (M_W : 8.0 & a_{max} : 0.271g) (c.f. Villavicencio, 2009) and (c) example of a post-seismic resistance map (top) and a Panda® liquefaction safety factor mapping (c.f. Lepetit, 2002)

Recently, as part of the assessment of the stability of Chilean tailings dams (Villavicencio, 2009; Villavicencio et al., 2010; Villavicencio et al., 2011; Villavicencio et al, 2012; Espinace et al. 2013a; Espinace et al., 2013b; Villavicencio et al., 2016), propose a study to estimate the CRR7.5 coefficient based on the dynamic cone resistance qd of Panda®. This method also builds on the work of (Robertson and Fear, 1998) by considering the relationship proposed by (Idriss and Boulanger, 2004). For the evaluation of the IC behaviour index, it is calculated from fines contents (%FC).

4. Conclusions

Dynamic penetrometer Panda® is a practical method, 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 of difficult access. Panda® represents today a very important advance in technology.

Studies carried out the last 30 years have made it possible to define correlations based on the cone resistance qd to assess orders of magnitude of soil geotechnical values as well as relationship with other geotechnical testing have been proposed.

References