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Servo-Assisted and Computer-Controlled Variable Energy Dynamic Super Heavy Penetrometer

Miguel Angel BENZ-NAVARRETE[a,1], Pierre BREUL[b] and Philippe MOUSTAN[a]
[a] *Sol Solution, Research & Innovation Department, Riom, France*
[b] *Institut Pascal, Civil Engineering, Clermont Auvergne University, Aubière, France*

Abstract. This paper describes a servo-assisted and computer-controlled variable energy super heavy penetrometer (DPSH) for dynamic cone testing denominated Grizzly-EV®. The equipment controls and adjusts the hammer driving energy as required depending on the penetration of the probe into to ground to maintain a relatively constant energy/settlement ratio throughout the test. Results of in-situ tests conducted at four different sites in France and Spain are used to assess the repeatability, sensitivity and reliability of the equipment. Comparisons to results of cone penetration tests (CPT) are also presented and discussed.

Keywords. Soil characterization, dynamic penetrometer, Grizzly-EV, ISO 22476-2, DPSH-CPT relationship, driving energy servo-assistance.

1. Introduction

The dynamic cone penetrometer (DCP) ISO 22476-2 [1] is a well-documented and widely accepted method for geotechnical site investigation. Among the different types of DPT, super-heavy dynamic penetrometers (DPSH) are preferred for deep test and when medium to very high consistency layers are present [2]. DPSH is particularly suitable for soils having a cone resistance value from 3 to 60 MPa (SPT blow number equivalent: $6 < N < 100$). On the contrary, in very soft soils, one blow can result in the tip of the cone penetrating into the soil 200 mm or even more. Therefore, DPTs measurements lose resolution, reliability and accuracy. Therefore, later calculations, as those obtained through correlations, will be affected.

In practice, these soft soil strata are of particular interest to the geotechnical engineer and reliable measurements are necessary in order to accurately characterize them. DPSH penetrometer used on soft and not compacted soil can also lead to premature deterioration or even breakage of automatic machines, as part of the hammer blow, inertial forces, will go to the drive mast and then to the machine's chassis.

In current practice using conventional hammer assemblies the operator overcomes this challenge adjusting manually the drop height of the hammer to maintain relatively constant driving energy. Considering the technical constraints, the use of DPSH is not recommended for loose, soft soil and/or saturated sands, silts and clays characterization.

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[1] Corresponding Author: Miguel Angel Benz-Navarrete, Research, Development and Innovation Department, Sol Solution, France; E-mail: mbenz@sol-solution.com.

(a) (b) (c)

Figure 1. The Grizzly® EV DPSH penetrometer (a) during a test [5] (b) PC mainframe and (c) drill & SPT. The Grizzly® EV can be equipped with a drill head (c) and also with an SPT corer. The extraction of the rods is integrated into the pile driver and the pile driver has an extraction capacity of 11Tm.

2. The Grizzly-EV® DPSH

Inspired by the Panda® penetrometer [3], (used for soil characterization [1] and compaction control [4] in France), the Grizzly®-EV is a computer-assisted, tracked penetrometer for dynamic variable energy DPSH testing [5]. The main characteristics of the device are summarized in Table 1. The measuring principle is that of a dynamic penetrometer. For each hammer blow, an automated numerical procedure is used to measure, calculate and record the cone penetration and calculate the dynamic cone resistance (q_d), using the modified Dutch formula (Equation 1). Penetration curve is displayed in real time on a computer screen. After the test, all data are stored, geo-positioned automatically and processed on site. These can be also sent and downloaded directly by GeoSprint software (included with the system), hence expediting preparation of the geotechnical report.

2.1. Instrumentation and control of drive energy

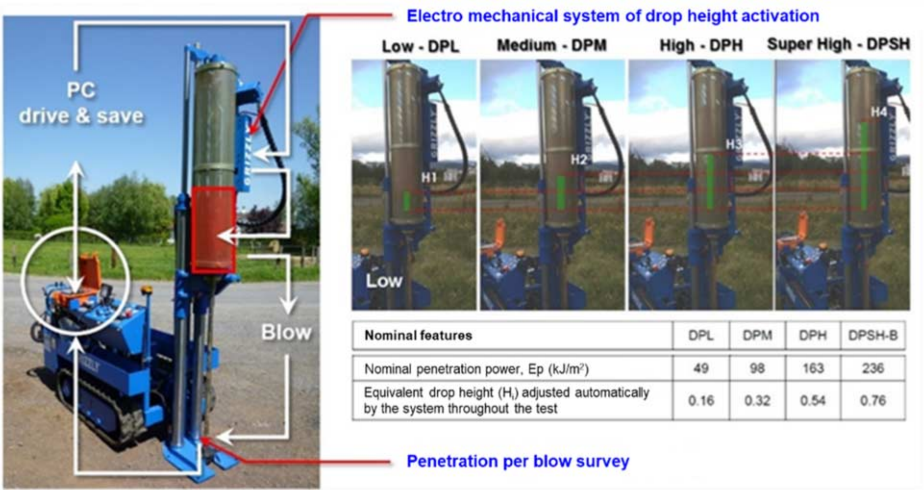
The device is equipped with an analog impact counter that triggers the penetration measurement performed with a displacement sensor with a resolution of 50µm (equivalent to an error of less than 1% over 10m depth). A second sensor is located close to the anvil to detect the drive mast descent and automatically position it. This allows to reduce the forces on the rods just before the next blow.

The mainly improvement and innovation incorporated to DPSH is the servo-assistance assembly. This include an electromechanical system as well as a series of sensors installed on the penetrometer drive mast in order to change the drop height of the hammer throughout the test automatically and in agreement with the drive energies indicated in the international standard ISO 22476-2 [1].

The on-board computer adjusts the driving energy for each blow by modifying the drop height of the mass based on the penetration of the previous blow. Hence, maintaining a constant energy/settlement ratio throughout the test. The drive energy is adjusted for each blow and it is based on variations of the drop height of the mass controlled automatically by the on-board computer (Figure 2).

Table 1. Features of the Grizzly®-EV DPSH Penetrometer.

Features and characteristics	*Value*
Weight of the mass, M (kg)	63.5
Drop height, h (m)	0.16/ 0.32 / 0.54 / 0.76
Beating energy min/max, Eb (Joules)	90 / 473.4
Rod diameter, dt (mm)	32
Section of the tip, $_{Ap}$ (cm^2)	20
Dimensions, L/W/H (m)	1.90 / 0.89 / 1.25
Machine weight, Ptotal (kg)	770 (empty) / 990 (full)
Extraction force, F$_{ext}$ (Tm)	11
Penetration power, Wp (kJ/m^2)	49 / 98 / 163 / 236



Nominal features	DPL	DPM	DPH	DPSH-B
Nominal penetration power, Ep (kJ/m^2)	49	98	163	236
Equivalent drop height (H_i) adjusted automatically by the system throughout the test	0.16	0.32	0.54	0.76

Figure 2. The Grizzly® EV DSH penetrometer - (a) on the left, Energy Control System and (b) on the right, the different drop height implemented and according to the standard (ISO 22476-2 [1]).

The drive energy is determined according to the penetration measured in the previous blow. The computer calculates instantly the value of height (H_i) for the next blow, adapting it to the soil resistance. Adjustments to the driving energy are applied to achieve a penetration per blow between 2 to 20 mm. More variations of soils resistance there are, more frequent will be the energy changes (Figure 3.b). Everything is done without any external operation on the machine as well as any interruption of the test.

The cone resistance q_d is calculated for each automatically using Equation 1. This is the best way to interpret a test of this type and that allows to consider the variations of energy [3, 6, 7]. It is also possible to display the penetration index I$_{DPB}$ or the blow N_i value. Indeed, as penetration inversely proportional to the driving energy [8, 9], the equivalent penetration index I_{r^*} can be calculated, with r^*: *DPL, DPM, DPH, DPH and DPSH energies*. This corresponds to the blow penetration that was obtained if a reference energy E_r had been used (Equation 2). It is also possible to compute (Equation 3) equivalent N_r value (N_{10}, N_{20}, N_{30}...).

$$qd = \frac{MgH_i}{Ae_m}\frac{M}{M+P} \tag{1}$$

$$I_{r^*} = e_m\frac{E_i}{E_{r^*}} = e_m\frac{H_i}{H_{r^*}} \tag{2}$$

$$N_{r\cdot}^{\;\;\cdot} = \frac{dS_{r\cdot}}{I_{r\cdot}} \tag{3}$$

where q_d cone resistance, M hammer weight, H_i current drop height adjusted by system for the next blow, H_{r} reference drop height, A cone section, e_m measured blow penetration and P driven mass. In equation 2, I_r is equivalent penetration index and E_i corresponds to the current driving energy. Also in equations 2 and 3 variables E_r, H_r, N_r and dS_r correspond respectively to the reference driving energy, drop height, number of blows and width of measurement trench defined as references values.

2.2. Measures processing and interpretation

The large amount of data provided by the equipment allows implementation of statistical signal analysis to better characterize penetration soil resistance, establish stratigraphic profiles and evaluate spatial variability [10]. Nevertheless, a minimal number of processing steps are recommended to improve the q_{d} profile with raw data. The authors recommend conducting first signal clipping to remove outlier followed by smoothing using a sliding moving method with a constant width (W_{j}) of 100mm (Eq. (4)). A signal regularization is also useful in order to explode final signal.

$$qd' = \frac{\sum qd_i \cdot e_i}{\sum e_i} \tag{4}$$

where qd' correspond to the output regularized signal, q_{di} to the cone resistance values within W_j and e_i is the measured penetration per each blow included to compute qd'. Furthermore, similar to the measured blow count in the SPT test, q_d, should be corrected for overburden pressure as follows [11, 12]:

$$qd_1 = qd \cdot C_N \; or \; qd_1 = qd' \cdot C_N \quad ; \quad C_N = \left(\frac{p_a}{\sigma'_{vo}}\right)^n \tag{5}$$

where q_d corresponds to the net cone resistance (MPa), C_N is a correction factor to account for overburden pressure, p_a is the atmospheric pressure (1 atm), σ'_{vo} is the effective vertical stress and n is a normalization exponent.

Besides, when working with a signal of N (Equation 3) it is advisable to correct the raw value N_{30} by energy efficiency (C_E), overburden pressure (C_N) and rods length (C_R) effects [8,9, 10, 11, 12, 13, 14, 15, 16]. C_N value is calculated according to Equation 5. Moreover, the work presented by [17, 18] establish the values of C_{E} and C_{R}. for Grizzly®-EV. An energy efficiency factor ER [13] of 85% and a C_E value of 1.4 is recommended by the authors. For C_R, corrections; it was recommended to use the expression proposed by [14] or an experimental curve [17, 18].

$$N_{1(60)} = N_{30} \cdot C_E \cdot C_N \cdot C_R \tag{6}$$

where $N_{1(60)}$ is the number value corrected by energy [16], overburden pressure and rod length effects [13]. This value can be correlated, based on existing literature, with that of the SPT. Figure 3 compares estimated $N_{1(60)}$ values from q_{d} measurements.

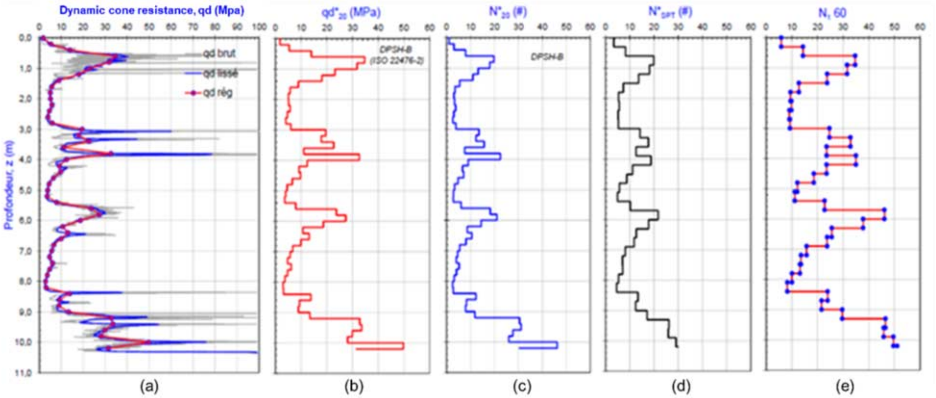


Figure 3. The Grizzly®-EV : Example of results raw and treated data after signal processing (a) raw, smoothed and regularized penetrograms field data, (c) $qd*_{20}$ regularization curve, (d) $N*_{20}$ curve, (e) correlated $N_{SPT}*$ *curve* and (d) SPT $N1_{(60)}$ curve corrected by energy and overburden pressure.

3. Experimental assessment

Four sites were chosen to verify quality, repeatability, sensitivity and reliability of measurements. These sites are in France (3) and Spain (1) and have interesting characteristics for this study such as (a) the presence of alternating very hard and very soft soils layers, (b) variable depth of investigation (3 to 25m) and (c) availability of in-situ data collected with other type of tests (e.g. CPTu and SPT).

3.1. Study of repeatability and sensitivity of measurements

The first experimental tests were carried out ta site in Gerzat (Auvergne, France) to evaluate repeatability and sensitivity of the equipment. Figure 4.c depicts the soil profile at the test site. At this site four dynamic penetration tests were performed within an area of 1 m^2. The sensitivity of the measurements is confirmed as all tests confirmed the presence of a layer of very loose soil clayey and sand at 2.5 m depth. The data presented in Figure 4 also shows good repeatability between measurements including the driving energy which is consistent with the variation in stiffness encountered during driving.

The second experimental site is also located in France. It comprises an embankment about 24 m high built with compacted layers of silty sand/gravel silty sand with thicknesses varying between 80 cm and 120 cm. Each layer was compacted with different compaction energies. The groundwater table is located 6.5 m below the top of the embankment.

A total of 5 penetration test were carried out along the structure with a spacing of about 60m between tests. Only the results of the four tests are presented herein (see Figure 5). Profiles of q_d values are presented in raw, smoothed and regularized format. Figure 5 confirms the sensitivity of the measurements to changes in stratigraphy related to variations thickness and compaction energy.

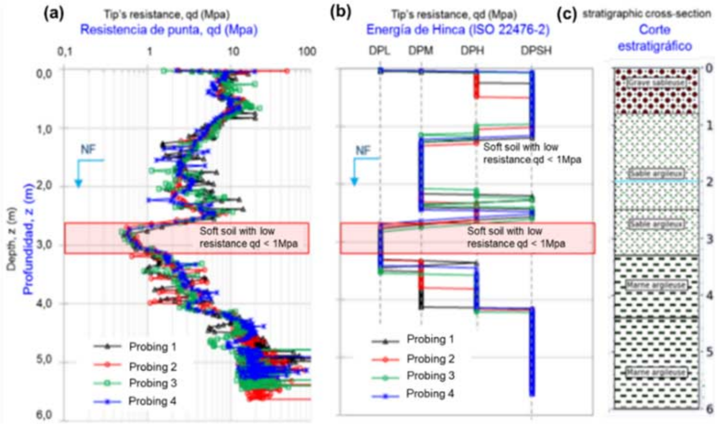


Figure 4. The Grizzly®-EV Repeatability and sensitivity of measurements (a) penetrometric curves obtained, (b) variation in threshing energy during drilling and (c) Gerzat's stratigraphic profile (France).

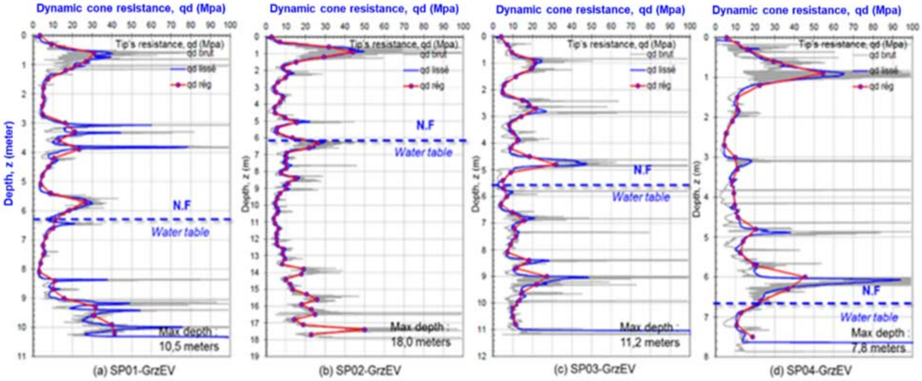


Figure 5. The Grizzly®-EV stratigraphic sensibility, embankment controlled in site 2 (France) - Test SP01 to SP04 profiles. A good agreement with the different layer thickness and resistance is showed, measurements are very sensitives to this changes in depth.

3.2. Comparative tests

Two additional sites were tested to assess the reliability of cone resistance *qd* measurements. At these two sites, several tests were carried out together (*Panda®, PMT, CPT, MASW...*). However, the main purpose of this section is to compare the results obtained with Grizzly-EV® are those obtained with the CPT.

Thus, the third experimental site is also find in France, in the commune of Aulnat. This is a fairly heterogeneous agricultural plot in depth. Here, 4 cone penetration CPTu tests were performed around the Grizzly®-EV dynamic penetration tests. The results obtained and their comparison are presented in Figure 6.

The fourth and last experimental site is located in Castelló d'Empúries, (Girona, Spain). It is a well-defined delta formation at depth, fairly homogeneous in space, of very low strength and involving a significant amount of geotechnical testing (CPTu, PMT, DMTs...) reported by [19, 20]. On this site, 6 Grizzly® EV penetration test were performed in the neighborhood of the two exist CPTu test. The nearest tests survey is compared between. Smoothing results obtained and its comparison is shown in Figure 7.

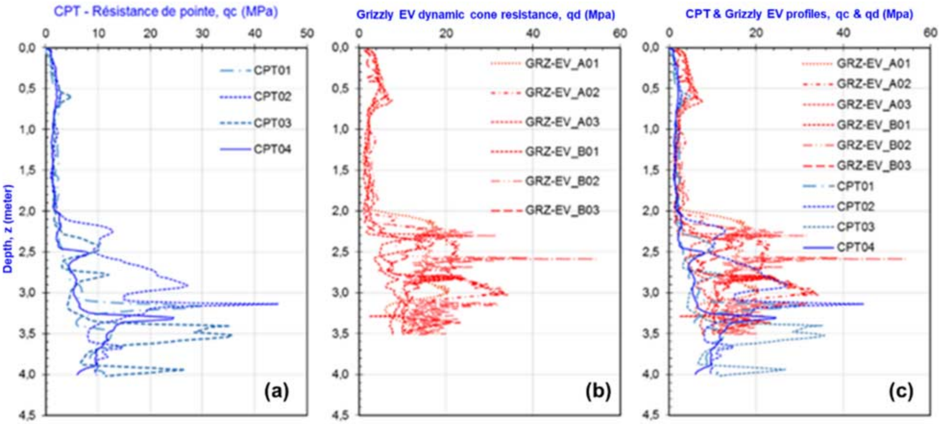


Figure 6. Reliability of measurements - site Aulnat (France) – Comparative & correlation tests Grizzly-EV® and CPT. A very good match with CPT profiles is found between 1,0 to 2,5m. Nerveless, for the backfill layer in surface (0 to 0.8m) as well as deep green marls (z > 2.5m), no good agreement is found.

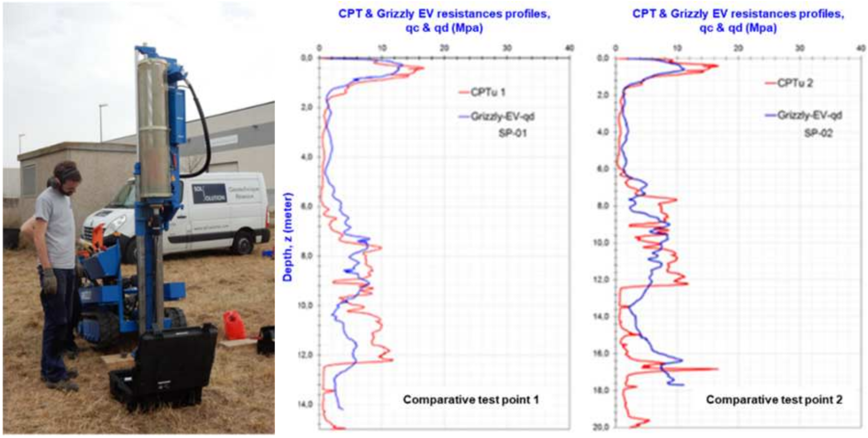


Figure 7. Grizzly®-EV tests - reliability of measurements - comparative with CPT test - Experimental site Castello d'Empuriés (Spain). CPT data, cone resistance qc, are plotted in red lines. Filtered data was used and a very good agreement with CPT profiles is found in all the depths, particularly in the soft soil layers. Heterogeneities in the soil profile are easily identifiable.

4. Comment and conclusions

Relevance and interest of the driving energy servo-assisted system. In all cases, when soil hardness or cone resistance variations were found, the servo-assisted system of Grizzly®-EV varied the driving energy correctly. No human intervention was needed.

Fine and high resolution measurements for soft soils. We were able to observe and highlight, particularly on the site in Spain, that Grizzly®-EV is very suitable for very loose and soft soils survey ($qd < 1MPa$ or N < 3) as well as to cross and characterize very strong soil layers ($qd > 50Mpa$).

Stratigraphic characterization. The high resolution of the measurements made makes it easy to identify soil layers as well as its thickness and compaction variations. These are one of the great assets that offers this new measuring system.

Repeatability and sensitivity of measurements. The high fineness of the measurement makes it possible to obtain highly reproducible and sensitive recordings in most cases. This was demonstrated in all experimental sites tested

Reliable measurements. Finally, the comparative tests with the cone penetration CPT test were carried out and the results are presented. A very good agreement was observed in all cases (Figures 6-7), as shown by [6, 7]. In fact, the adaptation of the driving energy to the consistency of the soil encountered during the survey, the device instrumentation associated to records and the use of the modified Dutch formula allow to obtain a qualitative and quantitative profile *qd(z)* of an important wealth. The result delivered by Grizzly®-EV are close to them obtained with CPT.

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