ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
v.24, n.7, p.497-502, 2020
Campina Grande, PB, UAEA/UFCG – http://www.agriambi.com.br

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v24n7p497-502

Development and validation of hydraulic driven electronic penetrometer for georeferenced point collection

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ABSTRACT: Soil penetration resistance (SPR) is used as an indicator of compaction, as it is related to important soil and plant attributes and is an easily obtainable measure. Its determination with the use of the penetrometer guides to the best soil management strategies, thus favoring crop development. The objective of this study was to develop and validate the georeferenced hydraulic driven electronic penetrometer, making it easier to obtain SPR. For this, 36 SPR readings from 0 to 0.60 m depth were performed with the manual and hydraulic penetrometers in two areas. The SPR results were analyzed by establishing the confidence intervals by the t-test ($p \leq 0.10$) at each 0.05 m depth and the georeferencing was analyzed through the root mean square error (RMSE). It was found that both penetrometers showed similarity in SPR measurement and in the georeferencing of the points.

Key words: soil management, soil penetration resistance, compaction

Desenvolvimento e validação de penetrômetro eletrônico com acionamento hidráulico para coleta de pontos georreferenciados

RESUMO: A resistência à penetração do solo (RSP) é empregada como indicadora da compactação, por estar relacionada a importantes atributos do solo e das plantas, e por ser uma medida de fácil obtenção. Sua determinação com o uso do penetrômetro orienta para as melhores estratégias de manejo do solo, favorecendo assim o desenvolvimento das culturas. O objetivo deste estudo foi desenvolver e validar o penetrômetro eletrônico de acionamento hidráulico georreferenciado, facilitando a obtenção da RSP. Para tanto foram realizadas 36 leituras de 0 a 0,60 m de profundidade da RSP com os penetrômetros manual e hidráulico em duas áreas. Os resultados de RSP foram analisados estabelecendo-se os intervalos de confiança pelo teste t ($p \leq 0,10$), a cada 0,05 m de profundidade, e o georreferenciamento através da raiz do erro quadrático médio (RSME). Constatou-se que ambos penetrômetros apresentaram similaridade na mensuração da RSP e do georreferenciamento dos pontos.

Palavras-chave: manejo do solo, resistência do solo à penetração, compactação

Editor responsible: Walter Esfrain Pereira
Ref. 218624 – Received 22 Jan, 2019 • Accepted 05 May, 2020 • Published 30 May, 2020

Introduction

Soil compaction is currently one of the problems that farmers have been encountering in their plantations, mainly caused by the intense traffic of agricultural machinery. Thus, soil properties are affected, directly interfering in crop development and affecting yield (Colombi & Keller, 2019).

Soil penetration resistance (SPR) is one of the direct ways of measuring compaction and is locally related to the attributes and conditions of the soil (Oliveira Filho et al., 2015). The most used method is cone index penetrometry, which determines the resistance of the soil against the penetration of a conical tip (Kotrocz et al., 2016).

Regarding the penetrometers available in the market, although the collection method is standardized by ASAE (2009), these devices have different systems, ranging from analog to electronic, and even collections with integrated geodesic coordinates, enabling the construction of compaction maps (Naderi-boldaji et al., 2016).

However, these different types of equipment may have heterogeneous data in the same field, influenced by the shape and projection area of the tip and the speed of penetration. According to Hoffer et al. (2015), the device's operator tends to stabilize the penetration speed when the rod reaches a depth greater than the subsurface one.

In order to expedite and reduce the efforts during collections of SRP, the objective of this study was to develop a hydraulic driven electronic penetrometer, aiming at constant rod penetration speed, integrated in a collection system of geodesic coordinates.

Material and Methods

The study was conducted at Universidade Federal do Paraná (UFPR), Ciências Agrárias sector, in the Laboratório de Adequação de Tratores Agrícolas (LATA), with the tests carried out at Fazenda Experimental Cangüiri (FEC).

A hydraulic driven electronic penetrometer (HEP) was developed to measure the SPR, according to Figure 1. The

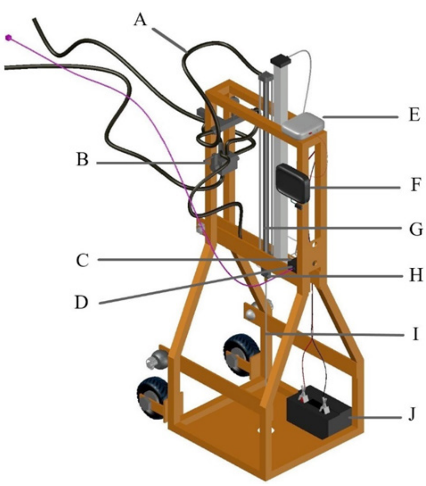


Figure 1. Hydraulic driven electronic penetrometer (HEP). (A) Hydraulic hoses, (B) hydraulic safety block, (C) wire potentiometer, (D) data acquisition system, (E) GNSS antenna, (F) display, (G) hydraulic cylinder, (H) load cell, (I) conical rod and (J) battery

structure was made of carbon steel designed to be attached to the three-point hitch of the tractor, and the hydraulic hoses (A) were designed to connect to the remote control valves (RCV) of the tractor.

The hydraulic flow from the tractor is directed to the hydraulic safety block (B) to control the expansion and retraction of the actuator in the hydraulic cylinder (G), vertically, aiming to introduce and remove the conical rod into the soil (I), the resistance (force) of the rod to the penetration into the soil measured by (H) a load cell, and the displacement speed (depth) of the rod through the (C) wire potentiometer attached to the hydraulic cylinder actuator.

The resistance and displacement data of the rod with conical tip along the soil profile are transmitted to the (D) data acquisition system (DAS), as the geodesic coordinates determined by the (E) Global Navigation Satellite System (GNSS). The device has a (J) 12-V independent battery and a display (F) to show the SPR.

The load cell (ZSL), IWM® brand, with a capacity of 5.0 kN, calibrated in hydraulic press, EMIC brand - PC200CS model, was installed between the hydraulic cylinder and the conical rod, resulting in a load cell pulse corresponding to 4.98 N (R^2 = 0.99). The displacement speed was measured by the nylon-coated steel wire potentiometer from Calt® (CWP-S1000V1) with length of 1.0 m. The sensor was calibrated with a millimeter ruler and each pulse emitted corresponded to 0.01 m (R^2 = 0.99).

The geodesic coordinates of the points where the SPR was measured were determined using a GNSS (Datum WGS 84), composed of the antenna AG-372 (Trimble®), connected to a Duinopeak model Shield, interconnected in the DAS.

The DAS was built on printed circuit board with the Atmega 2560 microcontroller (Atmel®) with 16.0 MHz clock, and a 12-V, 10-bit digital analog converter. The data acquisition frequency was every 0.01 m of the conical rod displacement, and the obtained data were directly saved on a hard disk for subsequent analysis.

The conical rod was made of stainless steel, with 9.53 mm diameter, type-2 conical tip, with base of 12.83 mm and 30° angle. The rod displacement speed toward the soil was measured before the tests at 30 mm s^{-1} (ASABE, 2012).

The hydraulic flow was supplied to the HEP through the RCV of the New Holland® tractor (T6050) with nominal power of 93 kW, equipped with a gear pump, with maximum flow rate of 70 L min^{-1}.

Soil penetration resistance (SPR) in the HEP was calculated by the cone index given by Eq. 1.

$$SPR = \frac{RF}{A \cdot 1,000,000} \quad (1)$$

where:

SPR - soil penetration resistance, MPa;

RF - resistance force of the conical rod penetration to the soil, N; and,

A - projection area of the cone (tip), m².

A commercial manual electronic penetrometer (MEP), from Falker®, PLG 1020 model, was used to compare the SPR measured by the HEP. This device indicates the conical rod displacement with sonar up to 0.60 m depth. This depth was used as a reference for both penetrometers.

The data collected by the MEP are stored in the internal memory of the device and then transferred to the computer via serial interface. The GNSS from Garmin® (MAP 64S) was used to collect the geodesic coordinates (Datum WGS 84) of the points where the MEP was employed.

SPR measurements with both penetrometers were performed in two areas, referred to as Area A and Area B. Area A has no vegetation cover and has no history of previous crops, being an area intended for the testing of agricultural machinery. Area B has a history of annual cultivation of corn for silage, being prepared in the conventional system (heavy harrowing + two light harrowing operations). The soil of both areas is classified as Inceptisol, with very clayey texture according to the particle-size analysis (Table 1). Soil density and volumetric moisture content were determined using the volumetric ring method (EMBRAPA, 1997), by collecting three rings at six depths (0-0.10; 0.10-0.20; 0.20-0.30; 0.30-0.40; 0.40-0.50 and 0.50-0.60 m), at five random points of Area A and Area B.

In the areas, a tape measure was used to previously demarcate 36 points, transversely and longitudinally spaced by 5 m, totaling 900 m². These demarcations corresponded to the points where the SPR was measured with the penetrometers.

The SPR readings and soil collections in Area A were performed on March 5, 2017, which had minimum temperature of 20 °C, maximum temperature of 31 °C and mean temperature of 25 °C, with relative humidity of 70% and precipitation of 1 mm. In Area B, the readings and collections were performed on April 23, 2018, which had minimum temperature of 13 °C, maximum temperature of 26 °C and mean temperature of 23 °C, with relative humidity of 61% and without rainfall (INMET, 2018).

For each penetrometer (HEP and MEP), 36 SPR readings were performed at the points demarcated in Area A and Area B, totaling 144 readings, resulting in the construction of four SPR curves (0-0.60 m depth).

The results of the SPR curves (spaced at 0.05 m) were analyzed by establishing the confidence interval by the t-test ($p < 0.10$), calculated using Eq. 2.

Table 1. Clay, silt and sand contents, at different depths, in Area A and in Area B

Area	Depth (m)	Clay	Silt	Sand
		(g kg⁻¹)		
A	0-0.10	663	87	250
	0.10-0.20	668	100	212
	0.20-0.30	668	74	238
	0.30-0.40	668	100	212
	0.40-0.50	672	93	235
	0.50-0.60	691	89	220
B	0-0.10	525	115	360
	0.10-0.20	535	80	385
	0.20-0.30	525	85	390
	0.30-0.40	570	65	365
	0.40-0.50	555	75	370
	0.50-0.60	560	60	380

Area A – No vegetation cover and no history of previous crops; Area B – History of annual cultivation of corn for silage

$$CI = \frac{(t\ SD)}{\sqrt{n}} \quad (2)$$

where:
- CI - confidence interval, MPa;
- t - tabulated value of t, $p \leq 0.10$;
- SD - standard deviation, MPa; and,
- n - number of repetitions (36).

To verify the accuracy between the GNSS devices used, the Root Mean Squared Error (RMSE) was determined according to Hallak & Pereira Filho (2011). For the calculations, the geodesic coordinates were transformed to UTM coordinates, and RMSE was calculated by Eq. 3.

$$RMSE = \left[\frac{1}{n}\sum_{n=1}^{n}(C_I - C_{II})^2\right]^{\frac{1}{2}} \quad (3)$$

where:
- RMSE - root mean squared error, MPa;
- C_I - UTM coordinate of GNSS I, of the HEP; and,
- C_{II} - UTM coordinate of GNSS II, of the MEP.

Results and Discussion

The results of soil penetration resistance obtained with MEP and HEP in Area A and Area B, as shown in Figure 2, are represented by SPR curves with similar trends along the profile.

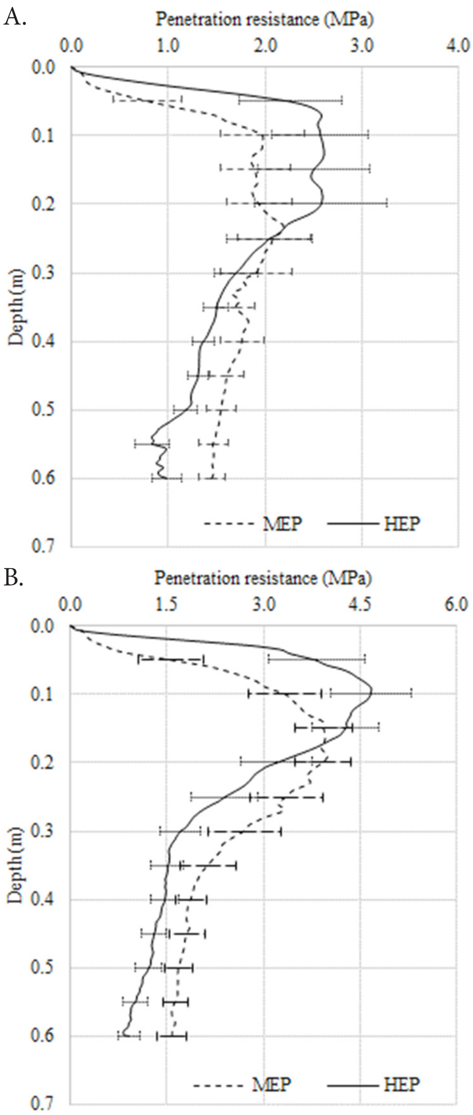
At the initial depths evaluated (0-0.05 m) in Area A and Area B, the confidence intervals differ, which may be related to human interference in the operation (Hoffer et al., 2015). In Area A, the confidence intervals demonstrated similarity of results at the depths (0.10-0.45 m), except for 0.40 m, and in Area B similar results were observed for the depths (0.15-0.25; 0.35-0.50 m).

Although the MEP indicated that the rod penetration speed is irregular (0.03 m s⁻¹), the operator had difficulty maintaining the regularity of insertion, as already mentioned by Molin et al. (2012). On the contrary, the HEP maintained the constant speed established by ASABE (2012), due to the hydraulic performance of the set (Masiero, 2013).

The higher SPR values obtained with MEP and HEP at the initial depths are related to the presence of a denser structure in the surface layers, which is common in most intensively cultivated soils, due to the intense traffic of agricultural machines (Roboredo et al., 2010; Lima et al., 2013a).

Table 2 describes the results of soil density and water content for Area A and Area B, respectively. It should be noted that the lower SPR values in the last layers is a natural tendency, as explained by Lima et al. (2013b), who reported increase in soil water content at these depths.

Soil penetration resistance is inversely correlated with soil water content due to the increase in cohesion forces between particles, resulting from the concentration of cementing agents and reduction in the lubricating effect of water (Bottega et al., 2011; Campos et al., 2013).



Area A – No vegetation cover and no history of previous crops and Area B – History of annual cultivation of corn for silage

Figure 2. Curves of soil penetration resistance à (SPR) along the profile, measured with manual electronic penetrometer (MEP) and hydraulic electronic penetrometer (HEP), and their respective confidence intervals

Table 2. Mean and standard deviation of soil density and water content in Areas A and B

Site	Depth (m)	Density ($g\ cm^3$)	Water content ($cm^3\ cm^{-3}$)
Area A	0-0.10	1.28 ± 0.06	0.34 ± 0.02
	0.10-0.20	1.16 ± 0.16	0.35 ± 0.05
	0.20-0.30	1.13 ± 0.18	0.39 ± 0.03
	0.30-0.40	1.13 ± 0.12	0.40 ± 0.05
	0.40-0.50	1.13 ± 0.18	0.40 ± 0.09
	0.50-0.60	0.98 ± 0.06	0.44 ± 0.02
Area B	0-0.10	1.24 ± 0.01	0.30 ± 0.01
	0.10-0.20	1.29 ± 0.02	0.34 ± 0.02
	0.20-0.30	1.09 ± 0.01	0.37 ± 0.01
	0.30-0.40	1.05 ± 0.02	0.37 ± 0.01
	0.40-0.50	1.03 ± 0.11	0.39 ± 0.03
	0.50-0.60	1.02 ± 0.11	0.40 ± 0.04

Area A – No vegetation cover and no history of previous crops; Area B – History of annual cultivation of corn for silage

The results of soil density in Areas A and B are within the values determined for agricultural soils, which range from 0.9 to 1.8 g cm^{-3}, according to Pereira et al. (2016). The correlations were positive in Area A (r = 0.894 for MEP and r = 0.889 for HEP) and in Area B (r = 0.987 for HEP and r = 0.945 for MEP) between soil density and SPR, results that are similar to those reported by Vogel et al. (2017).

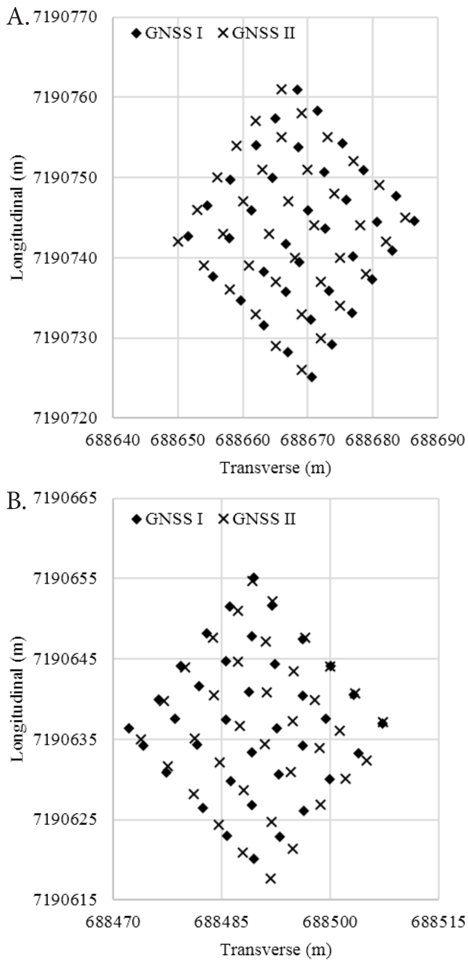
The soil water contents in Area A and Area B were within the range considered normal for SRP measurement, 0.25-0.45 cm^3 cm^{-3} for very clayey soils and 0.20-0.40 cm^3 cm^{-3} for clay soils (Molin et al., 2012).

The highest values of soil penetration resistance in Area A and Area B occurred in the first soil layers, where the water contents were lower, and the opposite occurred for last layer, which had the lowest SPR values, which was also found by Gubiani et al. (2014) and Ortigara et al. (2014).

Soils with higher clay contents tend to have high penetration resistance compared to sandy soils, due to the cohesion forces of particles and cementing agents, which in turn influence the available water capacity in the soil, interfering in SRP values (Mioto et al., 2016).

Clay content (Stefanoski et al., 2013) and type (Richart et al., 2005) interfere in soil resistance and resilience to compaction. Therefore, in more clayey soils, the loads on the surface act at greater depths, resulting in a thicker compacted layer of soil.

The maps of georeferenced points in Area A and Area B are shown in Figure 3. Table 3 presents the results of root mean



Coordinates on the longitudinal and transverse axes in UTM (Zone 22J)
GNSS I - HEP: Garmin® MAP 64S receiver
GNSS II - MEP: Duinopeak receiver interconnected to an AG-372 antenna (Trimble®)

Figure 3. Maps of georeferenced points in Area A - GNSS (I and II) (A) and Area B - GNSS (I and II) (B), with different types of GNSS

Table 3. Root Mean Squared Error (RMSE) of UTM coordinates determined with GNSS I and GNSS II in Area A and Area B

Site	RMSE (m)	
	Longitudinal	Transverse
Area A	0.87	1.96
Area B	3.16	1.97

Area A – No vegetation cover and no history of previous crops; Area B – History of annual cultivation of corn for silage

squared error (RMSE) for GNSS I (HEP) and GNSS II (MEP), in longitudinal and transverse directions.

The UTM coordinates of the points measured by the GNSS devices employed, in the penetrometers, showed RMSE less than 3.50 m (Table 3). Molin et al. (2015) report that, when collecting samples at a given point, one should work with a preset radius of 1 to 5 m, around the point, in order to dilute the error of the GNSS device used.

Conclusions

1. The manual and hydraulic penetrometers were similar in the measurement of SPR curves, despite showing different values in the initial and final soil layers evaluated.

2. The Global Navigation Satellite System (GNSS) of the hydraulic driven electronic penetrometer showed satisfactory results, being within the tolerable error.

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