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Economical hand-pushed digital cone penetrometer

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A b s t r a c t. The cone penetrometer is widely used in tillage and off-road mobility researches as an indicator of soil strength and density characteristics. Light-weight, manually operated units are especially useful in recording cone index determination at remote field locations. An electronic hand-pushed soil penetrometer with a microcontroller-based data logging system was designed and fabricated to provide a portable penetrometer for determining soil resistance to penetration in tillage studies. The device consists of three main components: a cantilever beam strain-gauge load cell held by housing to measure penetration force, depth measurement mechanism with a photodiode sensor, and a data logging system for amplifying, digitizing, and acquiring data. Data from the data logging system can be downloaded into a personal computer by an RS-232 cable and a software program. In evaluation stage, the performance of the developed penetrometer was compared with an Eijkelkamp hand-pushed digital penetrometer in controlled soil bin conditions. No significant difference was found ($p < 0.05$) between the two penetrometers. The penetrometer performance was reliable and the mechanical and electrical parts worked without any malfunction. The device is very light, easy to use and more economical compared to the conventional types.

K e y w o r d s: hand-pushed penetrometer, penetration resistance, load cell, data logging system

INTRODUCTION

In agricultural soil mechanics, the most relevant soil properties are the reactions of soil to applied forces (Rashidi *et al*., 2005). These properties are often called strength properties which for a given soil can change with time under the influence of climate, soil management and plant growth. The strength properties of any given soil and their change with time can be determined through the measurement of soil shear strength and penetration resistance whose values depend to a great extent on bulk density and moisture content. Soil penetration resistance is related to the pressure required to form a spherical cavity in the soil, large enough to accommodate the cone of the penetrometer, allowing for the friction resistance between the cones and its surrounding soil (Vaz *et al*., 2001).

Plant roots are less likely to enter soil layers with massive soil structure which are known to have higher soil strength. High mechanical strength in cultivated soil is developed because:

1) The soil has been compacted due to forces applied during traction and tillage by heavy agricultural machinery;

2) Particle aggregation has been partially lost by excessive tillage or organic matter losses; and

3) Soil cohesion has been increased by loss of soil water in the impeding zone (Bowen, 1981; Ohu *et al*., 1988; Sharifi *et al*., 2007; Tabatabaeefar *et al*., 2007).

Vehicle traffic, ploughing, disking, and soil-type can cause soil compaction. Levels in excess of 2 MPa can cause improper root growth or water drainage problems. These problems can lead to lower yields or wilted spots in the field (Price and Theriot, 2003).

Recording soil penetrometers have become common measurement devices for establishing profiles of soil resistance to penetration in studies of soil physical properties effects on plant growth. Their popularity could be attributed to the following reasons:

– they are quick, easy, and economical;
– they provide test data that can be analyzed easily; and
– they are good tools for investigating sands where undisturbed sampling is difficult (Perumpral, 1987).

Portable hand-pushed soil penetrometers are needed to enable such measurements in many field and plot areas where vehicle-mounted penetrometers can not be readily manoeuvred and positioned for multiple measurements.

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When coupled with current data logging systems, these measurement devices make detailed recording of soil resistance to penetration. Soil resistance to penetration is measured in terms of the 'cone index.' As described in ASAE standard S313.3, the cone index is the force per unit base area required to push the penetrometer tip into a specified very small increment of soil depth. Base area is defined as the cross-sectional area at the base of the cone. The cone is a 30 deg circular stainless steel cone with a driving shaft. The soil cone index is important in classifying terrain and the soil penetration resistance profile with depth for quantifying the level of soil compaction. (Boon *et al*., 2005; Tabatabaeefar *et al*., 2005).

Recent advancements in computer and digital technology have dramatically improved the practitioner's ability to collect, process, and analyze penetrometer data. Digital data loggers and depth measurement devices have enabled real-time association of raw data output with depth of penetration and calibration factors. It is now possible to predict soil bulk density, texture, moisture content, and colour in the field without taking a sample.

Many researchers have attempted to simplify the usage of the penetrometer by various complicated design concepts (Raper *et al*., 1999). Wells *et al*. (1981) designed a hand-held penetrometer by using a portable data logger with a companion magnetic tape memory for increased storage capacity. Morrison and Bartek (1987) designed a hand-pushed digital soil penetrometer which used a potentiometer with a torsional rewind spring and pulley for measurement of penetration depth and a strain gauge load cell for force. A version-5.4 Omnidate Polycorder data logger was used for collecting and saving the data. The total weight of the penetrometer and data logger was 4.7 kg for transport and positioning by a single operator. Garciano *et al*. (2006) designed and developed an instrumented portable device that measures shear, sinkage, cone index and friction properties of soil *in situ*. The instrumented portable device (Bevameter) is composed of a cone tip (ASAE standard small cone) that will provide cone index values with depth and, in addition, will measure soil-metal friction when the unit is rotated at desired depths. Moreover, the device also consists of a conical shear vane unit to measure soil shear characteristics at desired depths. Furthermore, it was equipped with an ultrasonic depth sensor to monitor the depth at which cone index, soil-metal friction, and soil shear characteristics measurements are obtained.

Probing rate and variations in that rate are not strictly controlled with hand-pushed soil penetrometers. The Rimike penetrometer gives an audible warning signal if probing rate exceeds the ASAE standard rate (Morrison and Bartek, 1987). Lowery (1984, 1986) found less variability in cone index with a constant rate tripod mounted penetrometer than with a hand-pushed model, but he also compared data recording resolution between solid state electronics and a mechanical stylus on a chart.

The objective of this work was to design, fabricate and evaluate the hand-pushed portable penetrometer used in tillage researches. This paper describes the methods of using it with a developed data logger and presents a comparison with a commercial Eijkelkamp (Model 06-15, the Netherlands) digital hand-pushed penetrometer.

MATERIALS AND METHODS

It is desirable to develop a penetrometer which could be manually transported and operated by one person at remote field locations. An additional requirement is that the device be able to electronically measure and record a large number of force data vs. penetration depth which would be individually identifiable. A final requirement is capability of penetrometer for transmitting data to a PC for further analyses.

ASAE standard S313.3 (ASAE, 2006) governs the design of the penetrometer probe tip and shaft. Two design sizes are recommended for use - 20.27 mm diameter base cone with 15.88 mm diameter shaft for soft soils, and 12.83 mm diameter base cone with 9.35 mm diameter shaft for hard soils. The smaller size was chosen for this hand-pushed soil cone penetrometer with driving shaft length of 60 cm and cone angle of 30° built and mounted beneath the load cell unit. The shaft and cone were machined from AISI 316 stainless steel. The unit was constructed so that the cone could be replaced when wear reduces the base diameter by 3%.

In order to measure the penetration force, a strain gauge cantilever beam load cell was designed and calibrated (Fig. 1). For measuring the cone index up to 4 MPa (maximum penetration force as 500 N by one person), a steel (AISI 4340 with modulus of elasticity as 207 GPa) beam with 110 × 50 × 4 mm in dimensions was selected as an elastic member. Two 120 Ω strain gauges were installed on the top surface and two identical strain gauges on the bottom surface (all oriented along the axis of the beam) of elastic member connected to a Wheatstone bridge with input voltage of 6 V DC provided by the data logging system. The transducer housing consisted of two sections so that it can protect the transducer. The top section of the housing provides the base connection for a lateral handle and the lower section, in addition to holding the cone shaft, maintains the alignment of the cone shaft with respect to the transducer (Fig. 2). Also, the housing provides 3 cm constraint for the load cell. The housing was built by machining a PVC (compacted type) block to lighten the weight of penetrometer. Two linear bearings were used to absorb the side forces. Under these circumstances, only the axial force of the cone shaft is transmitted to the transducer. In addition, a level device was used to maintain the perpendicular status of the penetrometer by operator. The housing was designed so that it can be used with another standard size cone (base dia. = 20.27 mm and shaft dia. = 15.9 mm) for soft soil. Before using the penetrometer unit, calibration tests were conducted for the load cell assembly. A 20 kN Tensile-Compression

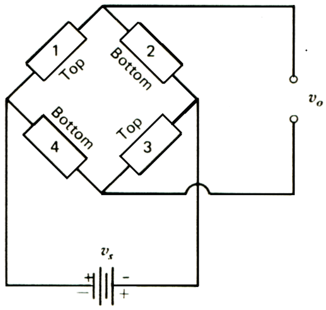

Fig. 1. Cantilever beam load cell (left) and Wheatstone bridge (right).

test machine (AMSLER, Germany) was used for this purpose. The average forces applied on the load cell from different tests were plotted against the voltage change of strain gauge bridge, measured with digital multimeter, and the result of regression analysis revealed a very good linear correlation. The sensitivity of the load cell was 500 mV kN^{-1} that is appropriate for this purpose. The accuracy of the load cell is ±0.25%. Also the strains of the gauges in loading and unloading stages were measured by a digital strain-meter and the average of hysteresis strain was calculated as 3.32 μm.

Several methods can be employed to obtain the depth signals. A linear variable differential transformer or a multi-turn potentiometer is used to obtain an electrical signal proportional to the depth of penetration. In this study, for depth mechanism design, a different method was employed by using a photodiode sensor, a 2 mm thick plate (700 x 30 mm) folded along the length forming L-shape, and a guiding block machined as shown in Fig. 2. On one side of the L-shaped plate, 55 holes (4 mm in diameter) were drilled equally at 10 mm intervals. The penetrometer shaft and the L-shaped plate were fitted into the machined guiding block so that the guiding block could move easily. The photodiode sensor was mounted on the guiding block so that the L-shaped plate could pass through the detectors (photodiode sensor) and interrupt the ultra-red rays passing from transmitter to detector. In order to sense the soil surface, a 10 mm thick-machined plate was positioned at the end of the L-shaped plate. When the bottom surface of this plate reaches the soil surface, the base of the cone is on soil surface. The number of output pulses of the photodiode sensor is representative of the depth (each pulse as 10 mm of depth). The total weight of the mechanical parts of the penetrometer is 6 kg which is lower compared to other available penetrometers since the frame is built from teflon material.

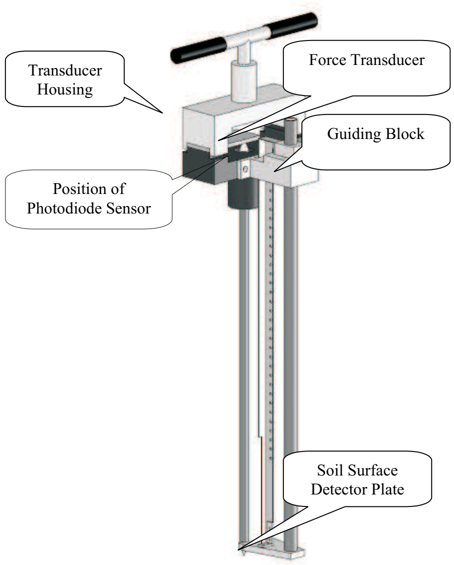

Fig. 2. Simulated model of the designed penetrometer.

A microcontroller-based data logging system (MBDLS) was designed and used for collecting, monitoring, saving and processing the penetration data (Fig. 3). An AVR microcontroller (ATMEGA 32, ATmel Company) was used for this purpose, with 32 KB flash, 2 KB RAM as well as 1 KB permanent memories. The maximum speed of data processing

Fig. 3. Data transferring from data logging system to PC.

is 16 MHz. The software was developed with CODEVISION AVR and standard C language. To eliminate the errors in designing the system circuitry, the PROTUES software was employed and, for final print of circuit with optimisation, the PROTEL DXP-2004 software was used. The instrumentation is powered from a rechargeable 6 V battery. The force and depth signals are generated by corresponding transducers installed on the penetrometer unit and sent to the data logging system.

The other features of the system are: (1) a 256 KB memory for saving the data of 300 insertions to depth of 55 cm, (2) a serial connection port to PC with RS-232 standard, (3) an A/D converter with 8 channels, one of which includes differential input and programmable amplifier with 1, 10, 100, 200 gain coefficients, (4) a 16-key keyboard along with 4 LED for displaying various working modes of the penetrometer, (5) hardware and software systems for noise elimination included an interrupting CPU clock in time of sampling from analogue input signal (hardware) and a soft-ware loop for replication and averaging the samples from 200 data points with a speed of 1 kHz, (6) software written in Visual Basic 6.0 to receive and download the registered data from memory of the system to PC, (7) a 40-column-4-line LCD to display all menus, and (8) possible accessibility to memory for editing, removing and observing the registered information. Data collected with data logging system are downloaded in six columns containing date, field number, block number, replication, penetration force and depth.

The evaluation of the penetrometer unit was performed in the soil bin of Agricultural Engineering Research Institute located in Karaj. The soil in the soil bin was classified as a clay loam with moisture content of 12% (w.b.). The soil was prepared with compacted layers in the middle depth of 10-20 cm by a soil processor unit. The developed penetrometer and a digital hand-pushed penetrometer (Eijkelkamp Model 06.15, the Netherlands) were employed in soil bin tests as shown in Fig. 4.

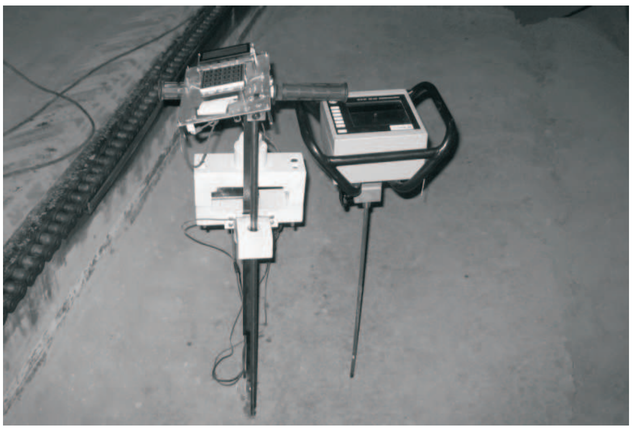

Fig. 4. Designed penetrometer (left) and Eijkelkamp penetrometer (right) in soil bin.

Prior to the beginning of the measurement process, the data loggers for the two penetrometers were programmed for use of a 30° (base area of 1.3 cm^2) cone and recording the penetration data resulting from 28 insertions. Eijkelkamp penetrometer has a S-shape load cell for measuring the penetration force and an ultrasonic sensor for determining the depth.

In the soil bin, soil penetration resistance measurements were made with the developed and standard hand-pushed penetrometers. Twenty-eight locations along the 14 m plot at 0.5 m intervals were selected for data collection with the two penetrometers. The Eijkelkamp penetrometer was set up to record data with an interval of 1cm to the desired depth (from 0 to 55 cm). The measurements by the developed penetrometer were made with a lateral distance of 10 cm relative to the points measured by Eijkelkamp penetrometer. Both penetrometers had a 30° cone angle and equal cone shaft diameter during the experiments. By dividing the force recorded to area of cone, the soil penetration resistance is obtained. The collected data were imported to a personal computer in laboratory and Microsoft Excel 2003 was used for statistical analysis (Fig. 3).

The system can be easily operated by one person in the field. Once in the field, the operator selects a site and follows the procedure outlined in this section. First, the operator checks the calibration equation of the force transducer and required penetration depth. In addition, information such as date, field number, block number and considered replications must be entered via the keyboard. The operator then selects data collection mode (which places the data logger on standby) and pushes the cone into the soil. As soon as the base of the cone reaches the soil surface, the first pulse – as an indication of zero depth – is sent by photodiode sensor. When the cone reaches to maximum depth, a question is asked for saving the data and by selecting YES, the data are saved into RAM. At the end of the measurement process, the data logger is connected to a personal computer with an RS-232 cable for data transfer. Before transferring the data, the download program (Penetrometer Data Recorder written by V.B. 6.0) is run in the PC. Then, the operator selects the data transfer mode and data are exported to PC and saved in an EXCEL file for further processing.

RESULTS AND DISCUSSION

To evaluate the performance of the designed penetrometer, laboratory tests for this penetrometer and the Eijkelkamp penetrometer were conducted and data obtained from these tests were compared.

Figure 5 shows the calibration result of the force transducer used in the designed penetrometer. It is evident that there exists an exact linearity ($R^2 \approx 1$) between the output voltage of the force transducer and the exerted force ranging from zero to 750 N. Thus, the output voltage of the force transducer serves as the reference signal to verify the penetration force.

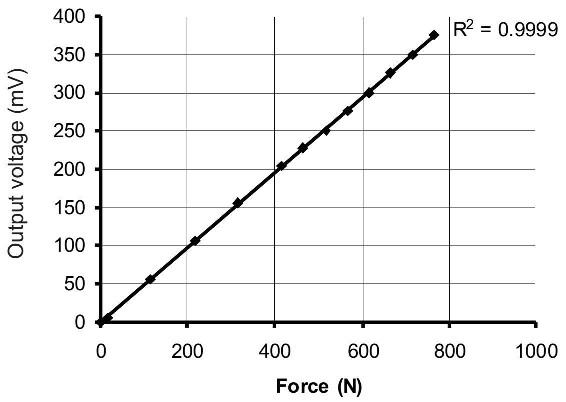

Fig. 5. Calibration plot of the load cell.

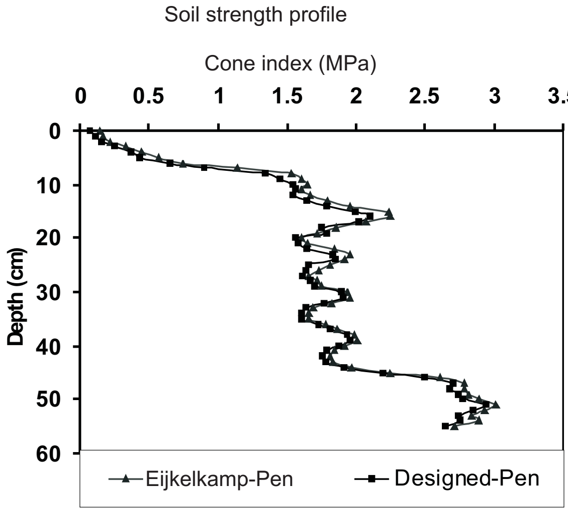

Fig. 6. Soil resistance plots for the two penetrometers at 12%(w.b.) soil moisture content.

The method used to determine the compatibility of the designed penetrometer was to compare its data with those obtained by Eijkelkamp penetrometer. The averaged penetration resistance measurements for 28 locations by both penetrometers were plotted for comparison at 10 mm depth intervals from zero to 55 cm (Fig. 6). This plot shows that similar trends were detected by both devices. This method was used by Tollner and Simonton (1989) for comparing a hand-pushed penetrometer with a penetrometer driven by an Instron testing machine.

Statistical analysis (t-test) was used for comparison of data obtained by the two penetrometers for soil penetration resistance (Table 1). The results of F-test showed no significant difference between the variances of two variables. Since the data samples had equal variances, the t-test analysis was run assuming equal variance. The presence of no differences between the data obtained from the field tests led to the conclusion that the soil resistance measurements for both hand-pushed penetrometers were similar as shown in Fig. 6. The soil resistance plotted for the two penetrometers is nearly identical. Also, the correlation between the two penetrometers was high with correlation coefficient of 0.997 and a slope close to one with an almost zero-intercept (Fig. 7). In order to verify the cone index values measured by a bevameter, Garciano *et al.* (2006) compared the instrument with a commercially available cone penetrometer. They found a high correlation between two penetrometers with coefficient of correlation of 0.970.

The average cone index-depth plot shown in Fig. 6 reveals that the compacted layers of the soil were at 10-20, and 50 cm of depth detected by the two penetrometers. One can discuss from this study and previous related works that higher soil resistance data is an indication of soil compaction increase and therefore a reduction in crop production yields due to lack of root growth. During the tests conducted, no mechanical or electrical problem was experienced. Using the penetrometer, one man can operate and collect data related to 30 insertions in 20 min.

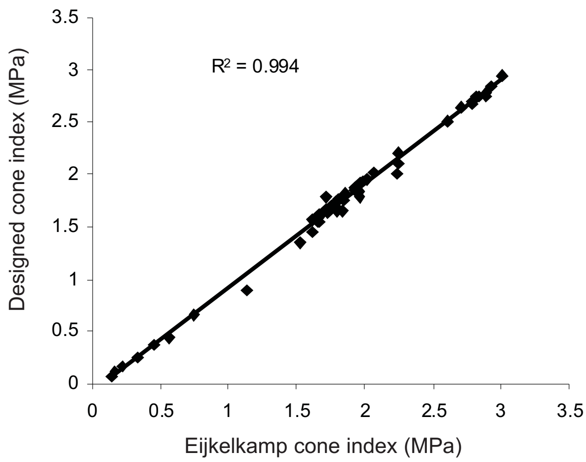

Fig. 7. Correlation between the two penetrometers.

T a b l e 1. t-test assuming equal variance

	Eijkelkamp-Pen	Designed-Pen
Mean (MPa)	1.820	1.730
Variance (MPa)	0.488	0.487
Observations	55	
df	108	
t	1.660	
Probability	0.255	

CONCLUSIONS

1. The use of an electronic data-logging soil penetrometer made it possible and convenient to gather digitized soil resistance data.

2. A digital hand-pushed soil penetrometer with a micro-controlled-based data logging system was designed and developed for measuring, displaying, and acquiring the soil penetration resistance in real time.

3. The penetrometer tested in this study has been proven good and can be used for performance evaluation of soil strength, trafficability predictions, and soil compaction.

4. The instrument required one operator and data storage capacity was approximately 300 insertions up to 55 cm of depth.

5. The required measurement depth determines the number of test data sets that can be stored on the data logger.

6. Required time for measuring cone index in 30 insertions to a depth of 55 cm was about 20 min, which was approximately equal to the time required by the Eijkelkamp penetrometer.

7. The experimental penetrometer appeared to be adequate for use in tillage studies operated at approximately the ASAE Standard rate for soils and conditions where the operator is able to push the probe into the soil without producing rate oscillations which would affect the cone index values.

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