2009

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Abstract. *The soil coulterometer is an "on-the-go" electro-mechanical system which collects impedance force data at multiple depths using an oscillating coulter. During the initial testing (summer 2006), only vertical soil impedance force data was collected using a pressure sensor. To improve the performance of the coulterometer, an extended octagonal ring transducer was integrated into the system to collect both the horizontal and vertical impedance forces given by the soil. In the summer of 2007, data was collected using the revised sensor from a typical central Kentucky field setting in a 0.8-ha (2-acre) plot. Four passes were made with the coulterometer. Seventy five coulter oscillations between depths of 100 mm (4 in.) and 305 mm (12 in.) were obtained for each pass. Ten standard cone penetrometer measurements were taken for each pass between depths of 100 mm (4 in.) and 305 mm (12 in.) using a multi-probe soil cone penetrometer. Three soil bulk density and water content measurements between depths of 100 mm (4 in.) and 305 mm (12 in.) in steps of 50 mm (2 in.) were taken for each pass using a nuclear soil moisture/density gauge. Simple linear regression analysis was used to find the relationship between coulter indices (kN/m), cone index (MPa), dry soil bulk density (Mg/m3) and water content (%).Coefficients of determination (R2) as high as 0.996 were obtained between coulter indices and dry soil bulk density measurements and 0.998 for coulter indices and water content measurements.*

Keywords. *Cone index, Coulter index, Soil compaction, Impedance forces, Soil Coulterometer.*

Crop yield variability in a field, in many cases, can be attributed to soil compaction. Soil compaction varies not only in different fields but also varies within a field (Raper et al., 2005). Over the years, many instruments have been developed to determine and mitigate soil compaction. A soil cone penetrometer (*ASAE Standards,* 1999) is typically used to measure soil strength and this value is recorded as a cone index which indicates the level of compaction in a soil. The tedious and time consuming nature of data collection by the soil cone penetrometer makes it an impractical instrument to measure soil compaction at a high resolution over a large field. Today's soil sensor research focuses on "on-the-go" soil impedance measuring devices. On-the-go impedance measuring devices measure soil cutting forces continuously, which correlate well with the soil strength indices and soil physical properties. Soil cutting forces are composite parameters which are dependent on soil physical properties like soil dry bulk density, moisture content and texture (Andrade et al., 2007).

Glancey et al. (1989) and Adamchuk et al. (2001) measured mechanical impedance of the soil using an array of strain gauges mounted on vertical rigid blades. Andrade et al. (2001) developed and tested a soil compaction profile sensor (PS), which is a direct measurement device. The device had independent cutting edges mounted on vertical wedges, which directly transfer forces to the load cells. Siefken et al. (2005) developed a multiple blade soil mechanical resistance mapping system (SMRMS) which can map soil mechanical resistance at three depths. Rooney et al. (2002) added a soil friction sensor and an optical probe to a hydraulically driven soil cone penetrometer. To measure the horizontal impedance force on-the-go, Alihamsyah et al. (1990) used a horizontal cone tip which tremendously improved spatial measurement density. Manor and Clark (2001) developed an instrumented wedge with a potentiometer which can move up and down while being pulled to determine the depth of the hard pan. An instrumented chisel was developed by Glancey et al. (1989) to measure soil mechanical resistance at different depths on-the-go. While the sensors discussed above offer much promise with regards to achieving reliable on-the-go measurement and mapping of soil compaction, they have potential liabilities with regards to required draft and problems caused by surface residue and disturbance of the soil surface. Pitla and Wells (2006) developed and tested the first version of an instrumented oscillating coulter to measure soil impedance. This device was conceived to minimize draft and soil disturbance while continuously measuring soil impedance with particular emphasis on use for no-till cropping. The principal force sensing element of soil coulterometer is the extended octagonal ring transducer

Submitted for review in September 2008 as manuscript number PM 7727; approved for publication by the Power & Machinery Division of ASABE in July 2009.

This article (09-05-064) resulted from research sponsored by the Kentucky Agricultural Experiment Station and was funded in part by a grant from the USDA Special Grants Program. Mention of trade names is for information purposes only.

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  ISSN 0883-8542

(EORT). The first version of extended octagonal ring transducer was developed by Godwin (1975) to simultaneously monitor horizontal, vertical forces and moment in the plane of these two forces. A double extended octagonal ring transducer was developed by Chen et al. (2006) to measure the drawbar dynamometer forces. This manuscript focuses on the integration of an extended octagonal ring transducer (EORT) and the soil coulterometer.

Objectives

The objectives of this study were:

- To fabricate, calibrate, and test an extended octagonal ring transducer (EORT).
- To develop and evaluate an instrumented vertically-oscillated disc coulter system capable of mapping vertical and horizontal resistance forces simultaneously under field conditions.
- To correlate coulterometer indices with standard soil properties (cone index, dry soil bulk density, and water content) and there by assess the ability of the coulterometer to characterize soil compaction state.

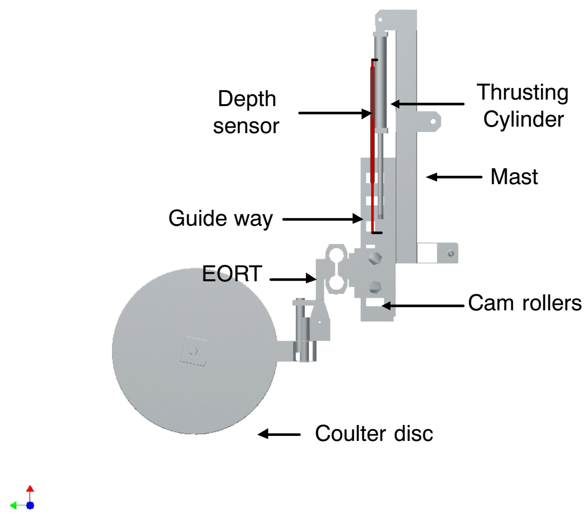


Figure 1. Soil coulterometer.

Materials and Methods

Soil Coulterometer

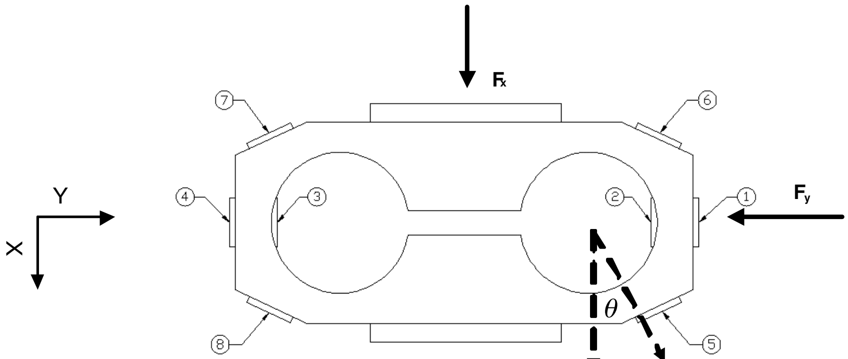
The system designed and developed for this research study is shown in figure 1. The soil coulterometer consists of an 810-mm (32-in.) diameter coulter disc which oscillates up and down with amplitude of 203 mm (8 in.) and collects soil impedance force data with the aid of an extended octagonal ring transducer (EORT). The oscillation motion of the coulter disc is provided by a hydraulic cylinder and an electro-hydraulic directional control valve. Cam rollers are housed in vertical linear guide way and facilitate the smooth operation of the assembly. The soil coulterometer is mounted to the three point hitch of a tractor with the aid of vertical mast and the center link. Real-time depth measurements from a depth sensor and the impedance forces generated as a result of soil-tool interaction measured by the EORT were recorded to a PC. A PMD 1208-LS data acquisition module (Measurement Computing Corp., 2006) with 12-bit A/D conversion capability was used for performing analog to digital conversion of the sensor data from EORT and depth sensor. Digital channels of the data acquisition module were used to actuate the solenoid valves of the directional control valve of the actuating cylinder. A Visual Basic 6.0 application program (Microsoft Corp., 2006) was developed to control the vertical motion of the coulter and store the digitized data from EORT and GPS.

Extended Octagonal Ring Transducer

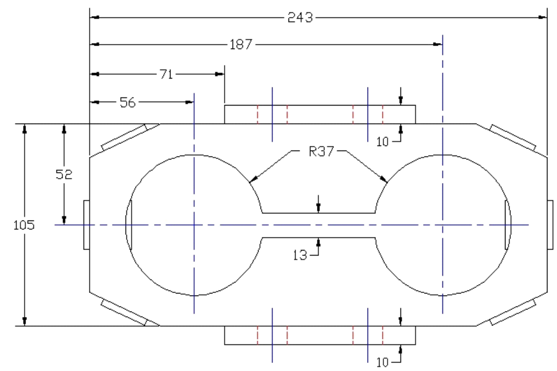
An EORT was used to measure the horizontal and vertical reaction forces generated from soil tool interaction in the field. The design parameters of this transducer are derived from the research work of Godwin (1975). The EORT consists of a machined block made of AISI 1045 alloy steel (fig. 2). The transducer was heat treated to improve the tensile strength characteristics. A total of eight strain gauges manufactured by Micro Measurements Division (Malvern, Pa.) were used. The strain gauges measured single axis strain and had a nominal resistance of 350 Ω.

Strain Nodes and Gauge Placement

Two sets of four strain gauges (1, 2, 3, 4 and 5, 6, 7, 8 – fig. 2) were bonded to the octagonal-machined steel block to measure the applied horizontal and vertical forces (fig. 2). Each set of strain gauges was connected in a Wheatstone bridge arrangement and the strain gauges were bonded at specific locations on the steel block known as horizontal and vertical strain nodes. Horizontal strain nodes (1, 2, 3, 4) are the locations on the transducer where the strain is produced directly in proportion to the application of horizontal force and vertical strain nodes (5, 6, 7, 8) are locations on the transducer where strain is produced directly in proportion to the application of vertical force. The location of strain nodes for mounting the strain gauges were taken from Cook and Rabinowicz (1963). The angular positions of vertical and horizontal strain nodes were found to be $\theta = 50°$ and $\theta = 90°$ from the horizontal axis of the ring respectively. Illustration of direction of application of horizontal force (F_x), vertical force (F_y), and the locations of strain gauges is provided in figure 2. Siemens (1963) used the node locations proposed by Cook and Rabinowicz (1963) when bonding the strain gauges to an extended octagonal ring transducer. He reported that bridge outputs with respect to loading were linear. Godwin (1975) observed that when the tine or wedge was directly bolted to the transducer, the calibration showed a linear relationship between the output from force bridge measuring F_x and applied load, but the output from force bridge was not independent of the position of the force, i.e. output from the wheatstone bridge circuit changed with position of the applied horizontal force even when the force applied was constant. To compensate for position sensitivity of the transducer, Godwin placed thin steel plates with a thickness of 10 mm (0.38 in.) on each side of the transducer as shown in figure 2. He found that with this modification, the transducer was insensitive to the location of F_x. This implies that a constant horizontal force application at all points on the center line of the transducer extension will result in the same



(a)



(b)

Figure 2. (a) Extended octagonal ring transducer strain gauge locations (top); (b) Dimensions (mm) (bottom).

force. Thus, the transducer's output should be independent of the point of force application.

Calibration

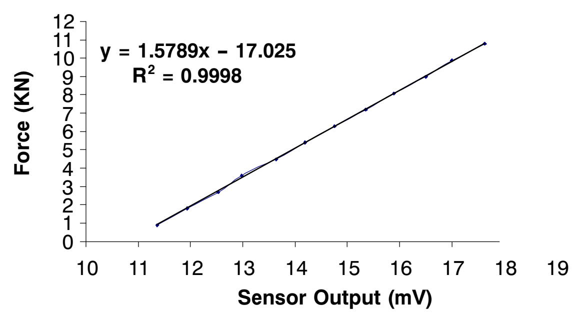
Calibration of the EORT was done using a universal testing machine (UTM). The transducer was calibrated separately for horizontal and vertical forces. A special adapter was made to mount the transducer on the universal testing machine for the calibration procedure. The sensor was calibrated by applying forces in horizontal direction ranging from 0.890 to 10.66 kN (200 to 2400 lb) in steps of 0.890 kN (200 lb) and 0.890 to 6.286 kN (200 to 1400 lb) in steps of 0.890 kN (200 lb) in vertical direction. The precision of UTM was 0.445 N (0.1 lb)

The horizontal and vertical calibration curves were linear with coefficient of determinations, r^2 = 0.999, 0.999 respectively, as shown in figure 3.

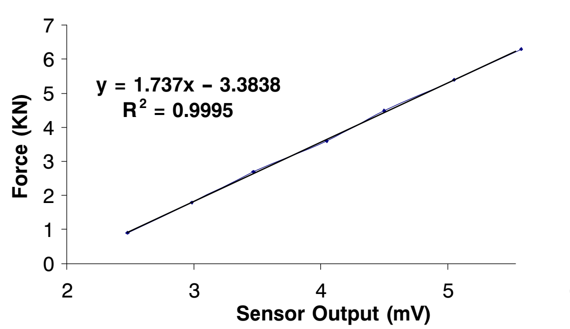
Data Collection and Field Testing

Testing of the coulterometer was done at the University of Kentucky's Animal Research Center (UKARC). A 0.8-ha (2-acre) test plot was used in this study. The coulterometer was operated at a nominal tractor speed of 1.6 km/h. Four passes were made with the coulterometer in the test plot. The coulter disc oscillated between depths of 100 and 300 mm (4 and 12 in.) and the EORT sensor output signals were digitized to quantify horizontal (F_x) and vertical (F_y) impedance reaction forces of the soil. The data collection scheme and operation of coulterometer during the field test is illustrated in figure 4.

Spatial coordinates of the impedance forces were recorded using a Trimble AgGPS unit. Data from the sensors



(a) Horizontal forces



(b) Vertical forces

Figure 3. EORT sensor calibration curves for horizontal forces (left) and vertical forces (Right).

were collected at a frequency of 10 Hz. A hydraulically driven multi-probe soil cone penetrometer was utilized in this study (see fig. 5). Force transducer readings for each probe were recorded simultaneously with depth transducer

Figure 4. Data collection scheme (left); soil coulterometer operation during field data collection at UKARC (right).

output. Cone index values for each probe were calculated for 50-mm (2-in.) depth increments. A dual probe gamma/neutron soil moisture density gauge manufacture by CPM Corp. (Martinez, Calif.) was used to measure soil bulk density and water content. Vertical access holes spaced 30.5 mm (12 in.) apart were prepared by a special tractor – mounted apparatus (see fig. 5). Gamma/neutron sources and corresponding detectors were lowered into the respective holes to secure bulk density and water content measurements in 50-mm (2-in.) depth increments.

Ten standard cone index measurements were taken for each pass between depths of 100 and 300 mm (4 and 12 in.). Three soil bulk density (ρb) measurements were taken in each pass using the nuclear density gauge. A total of 40 cone penetrometer measurements and 12 soil bulk density measurements were taken to characterize the soil condition of the entire plot. Seventy-five (75) coulterometer

Figure 5. Multi-probe soil cone penetrometer (left) and nuclear density testing machine (right).

oscillations were obtained for each pass and soil impedance data was collected between depths of 100 and 300 mm (4 and 12 in.). Each oscillation of the coulter enabled the coulterometer to collect data twice at all depths between 100 and 300 mm (4 and 12 in.).

Results and Discussion

One-hundred and fifty (150) horizontal and vertical force measurements were averaged at each depth between 100 and 300 mm (4 and 12 in.) for every pass as the coulterometer measured forces, twice for each oscillation. The horizontal impedance force or the draft force was found to increase with the depth of operation of the coulter as expected. Similar trend was observed for the vertical impedance forces. For the entire first pass, at all depths of operation, the vertical impedance forces were higher than the draft forces. Comparison of the average impedance forces was made and it was observed that at all depths of operation the average vertical forces were higher than the average horizontal forces (fig. 6).

Coulter Indices

Two indices, known as coulter indices, were determined from the impedance forces and depth of operation measurements obtained from the coulterometer.

$$CUIH = Fxd / d \quad (1)$$

$$CUIV = Fyd / d \quad (2)$$

where
CUIH = horizontal coulter index
CUIV = vertical coulter index
Fxd = average Horizontal impedance force or Draft force (kN) at depth d, for a complete pass
Fyd = average Vertical impedance force (kN) at depth d, for a complete pass
d = depth of operation of the coulter (m)

The coulter indices were determined by dividing horizontal and vertical force by the depth of coulter penetration. Soil cutting resistance would only be sensed on the front of the blade, thus the rear blade perimeter should

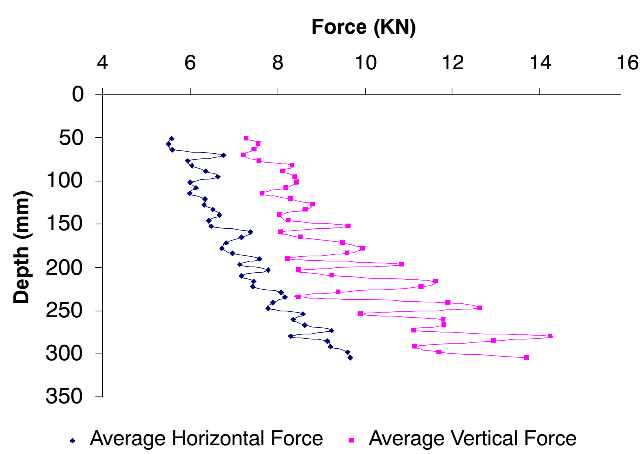


Figure 6. Comparison of average horizontal force and average vertical force profiles in first pass.

have little effect on either force. Similarly, the area of coulter in contact with soil should have little effect on the blade forces because the soil/blade friction is negligible when compared to the cutting force sensed at the front edge of the disc. When towing the coulter in soil the rotating disc cuts the soil using its front edge and loosens the soil, which may result in reduced soil/blade friction. Also the buildup of lateral forces on the coulter is avoided as the coulter is allowed to pivot about the yaw axis. Thus, depth was considered instead of perimeter to determine the coulter indices from horizontal and vertical forces.

Comparison of variation of average CUIH and CUIV with depth of operation of the coulterometer in the first pass is depicted in figure 7. It was observed that CUIH and CUIV decreased with depth of operation and the magnitude of CUIV at all depths was higher than CUIH. To characterize soil compaction of the entire field, standard soil parameters which effect soil compaction, i.e., cone index, dry soil bulk density, and water content, were considered for analysis. Dry soil bulk density was observed to decrease with depth and water content of the soil was observed to increase with depth. The average dry soil bulk density and water content profile is shown in figure 8. Similar trends were observed for all the other passes.

The coefficient of determination between CUIH and dry soil bulk density was found to be 0.930 for the data obtained during the first pass. Note that experimental data lie within 95% confidence interval for the first pass. Hence, there exists a strong relationship between both the parameters and 93% of variation in dry soil bulk density can be explained using the CUIH. It was observed that the vertical coulter index also correlated well with the dry soil bulk density with a coefficient of determination of 0.875 for the data obtained during the first pass. Once again, the observed data lies within 95% confidence interval in the first pass. Similarly the correlation analysis was done for all the passes and it was found that the coefficient of determination (r^2) between coulter indices and dry soil bulk density were high.

The r^2 values between coulter indices and dry soil bulk density for the entire field was found by averaging the coulter index measurements and dry soil bulk density measurements from individual passes at same depths. Table 1 gives the summary of r^2 values.

The coefficient of determination r^2 between CUIH and water content in first pass was found to be 0.983 which indicates a strong relationship between the water content and

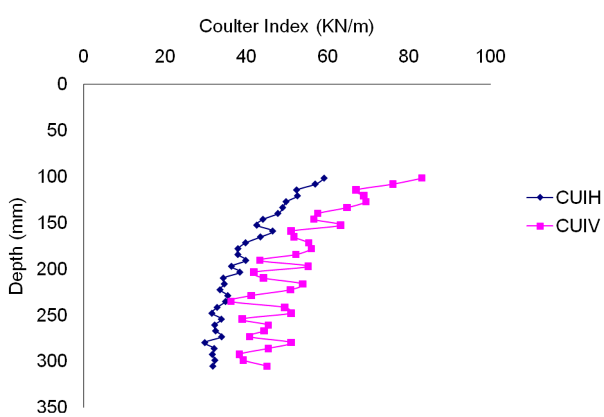


Figure 7. Variation of coulter indices with depth of operation.

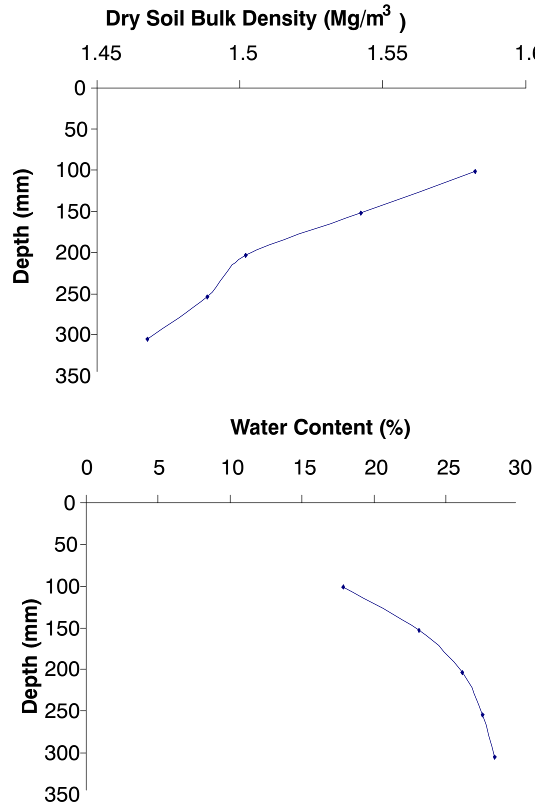


Figure 8. Variation of dry soil bulk density (left), variation of water content (right).

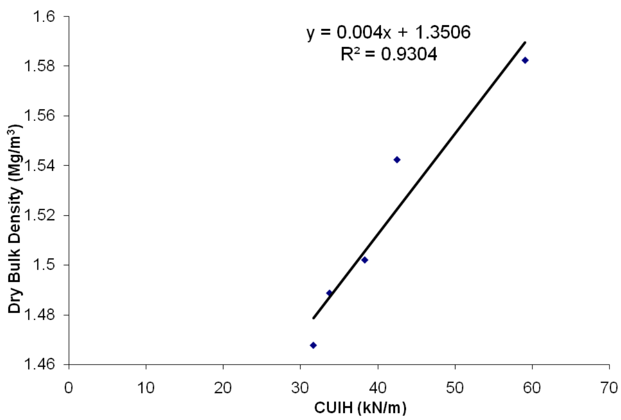
the CUIH. Coefficient of determination between CUIV and average water content in the first pass was found to be 0.932. Once again all the observed data fell within 95% confidence intervals which indicates a very good fit between both the parameters. Thus 98% of variation in water content can be explained by CUIH. Similarly, correlation between coulter indices and water content for the complete field was done by averaging the coulter indices and water content from all the passes. The overall r^2 value between average horizontal coulter index and water content was 0.990 and that between average vertical coulter index and water content was 0.997.

Conclusions

Application of simple linear regression on the data collected by soil coulterometer indicated that it is possible to predict standard soil parameters like dry soil bulk density and water content from coulterometer indices. Coefficients of

Table 1. Coefficient of determination (r^2) between coulter indices and average dry soil bulk density.

Field Pass No.	Coefficient of Determination (r^2) between CUIH and Average Dry Soil Bulk Density	Coefficient of Determination (r^2) between CUIV and Average Dry Soil Bulk Density
First pass	0.930	0.875
Second pass	0.975	0.865
Third pass	0.979	0.985
Fourth pass	0.989	0.836
Complete field	0.983	0.996



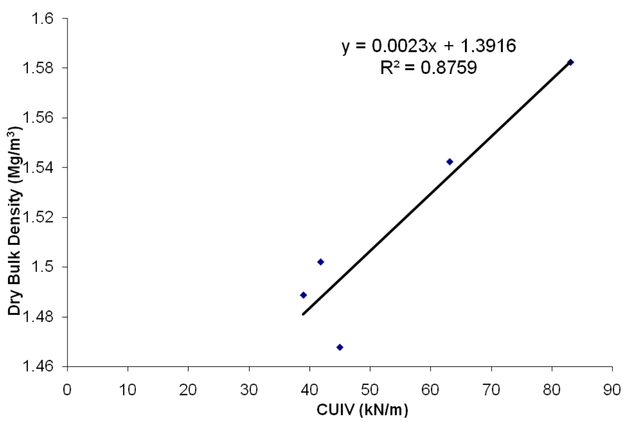


Figure 9. Typical simple linear regression results: Dry bulk density and CUIH (left), Dry bulk density and CUIV (right).

determination obtained were high between coulter indices and dry soil bulk density and coulter indices and water content, both indicative of strong relationship. Extensive data needs to be collected and analyzed before asserting the validity of soil coulterometer in identifying soil compaction. Soil coulterometer has a good potential for application in no-till farming situations which require minimal disturbance of soil layers. Large amount of soil strength data at multiple depths can be collected in a short time with reduced effort which can reduce fuel and energy costs.

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