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DEVELOPMENT OF AN INSTRUMENTED DEEP−TILLAGE IMPLEMENT FOR SENSING OF SOIL MECHANICAL RESISTANCE

V. I. Adamchuk, A. V. Skotnikov, J. D. Speichinger, M. F. Kocher

ABSTRACT: Variable−depth tillage has the potential for economic and environmental benefits to modern crop production. Varying tillage depth according to local soil conditions prevents the waste of energy and preserves soil ecology. A prototype instrumentation system was developed based on a conventional implement for deep tillage. It was equipped with two load cells and two sets of strain gauges for sensing the load applied to the implement during tillage. Two linear pressure distribution models (full and redundant) were used to describe the change of soil mechanical resistance with depth. These models were then used to compare estimates of soil mechanical resistance applied to the point of the deep−tillage implement based on predicted and measured values. Field evaluation was conducted to illustrate the system’s performance in two experimental sites. In both cases, instrument predictions corresponded with soil profile measurements obtained using a standard cone penetrometer. The developed system may become a part of variable−depth tillage equipment after an algorithm for a closed−loop tillage depth control is developed.

Keywords: Mechanical resistance, Precision agriculture, Soil sensors, Variable−depth tillage.

Regions of high mechanical resistance in the soil may arise naturally, by compaction from heavy farm machinery, or by the formation of plow pans. Compacted soils with high strength reduce growth rates of crop roots and thus limit the acquisition of water and nutrients by the plant. This may affect crop yield and require tillage practices to reduce soil compaction (Bengough, 1991).

Advances in site−specific crop management (precision agriculture) provide the capability to vary a soil treatment across an agricultural field. Soil tillage is one such treatment. Although conventional methods of crop management provide similar soil conditioning across the entire field, different parent material, topography, and past management can cause a significant variability in soil compaction. Therefore, local (spot) or variable−depth tillage may increase the efficiency of this field operation. By avoiding tillage of soil with a relatively low level of compaction, both economic and environmental improvements in crop production can be achieved through: (1) reduction of energy waste, and (2) preservation of soil structure.

Soil compaction is related to several physical and mechanical characteristics and is defined as “the volume change produced by momentary load application caused by rolling, tamping, or vibration” (Bradford and Peterson, 2000). Measurement of the mechanical resistance of soil to a penetrating object is recognized as a conventional method to estimate the level of soil compaction. ASAE has specified a soil cone penetrometer as the standard method to determine a soil strength index from a point penetration test (ASAE Standards, 2002).

Even when automated, cone penetrometer measurements are time consuming and highly variable from point to point (Campbell and O’Sullivan, 1991). On−the−go measurement of soil mechanical resistance, however, allows for a substantial increase in measurement density. A number of prototype systems have been developed to map soil mechanical resistance on−the−go. Some of them have been used to determine horizontal soil resistance at a particular depth (Liu et al., 1996; Alihamsyah et al., 1990; Hall et al., 2000); others were developed to quantify different operational parameters associated with implement draft performance (Owen et al., 1987; Mouazzen et al., 2003). These systems are useful while mapping the variability of soil resistance; however, measurements at multiple depths are needed to prescribe variable−depth tillage. Several prototype systems (Andrade et al., 2001; Adamchuk et al., 2001; Chung et al., 2003) have been developed to determine both spatial and depth variation of soil resistance. Manor and Clark (2001) designed an instrumented subsoiler to map hardpans using dynamic operation of the implement. The maps obtained could be used to prescribe variable−depth tillage in different places within a field. A control system such as the one developed by Khalilian et al. (2002) could then be used to guide the tillage equipment to the appropriate depth.
Although defining proper tillage depth in various soil conditions remains a researchable issue, real-time control of tillage implements can be performed if an assessment of the vertical distribution of soil mechanical resistance is accomplished at the time of tillage. Therefore, it seems reasonable to combine a measurement system with a tillage implement to provide supplemental inputs for real-time control of variable-depth tillage equipment.

The goal of this research was to develop an instrumentation system based on a commercial implement for deep tillage that could identify changes in soil mechanical resistance with depth.

MATERIALS AND METHODS

SYSTEM DESIGN

An instrumented deep-tillage implement has been developed and tested (fig. 1). A commercial straight standard (N261127, John Deere Tillage Division, Des Moines, Iowa) was used to house the instrumentation system. A custom point and a protective shin were designed to better cover the installed transducers. The custom point was also used to minimize the effect of soil disturbance on the protective shin. The instrumentation system included two washer-type load cells (LC901–3/8–10K, Omegadyne, Inc., Sunbury, Ohio) and two sets of strain gauges (EA–06–250PD–250–W, Measurements Group, Inc., Raleigh, N.C.) configured in a bending beam Wheatstone bridge. Both load cells were installed on the inner surface of the protective shin (fig. 1) and carried the entire load applied to the shin while tilling. One set of strain gauges was attached to the standard between the two load cells, and the other set was installed immediately below the mounting bracket.

The load cells were used to determine the linear trend (gradient) of topsoil resistance pressure change with depth. The strain gauges, on the other hand, measured the strain caused by the bending moment produced by the load transmitted through the load cells as well as by the load applied to the point. Therefore, two linear distributions modeling the change of soil mechanical resistance with depth could be derived: one model for the shin, and the other for the point. By overlapping both models, two estimates of soil mechanical resistance pressures at the same depth can be determined. If the depth of the point of the deep-tillage implement is used, the soil mechanical resistance calculated based on the distribution developed for the shin can be referred to as the “predicted” resistance. At the same time, the estimate based on the linear distribution of the soil mechanical resistance pressure acting on the point can be referred to as the “measured” resistance. Inconsistency in the real soil profile (i.e., the rate of change of soil mechanical resistance with depth is variable) will produce a disagreement between the predicted and measured soil mechanical resistance pressures. Figure 2 illustrates scenarios of a deep-tillage implement operated in a field with an existing local maximum of soil mechanical resistance (hardpan). In this example, shallow, appropriate, and deep tillage operations are defined through the difference between the measured and predicted soil mechanical resistances applied to the point. As shown in the figure, increased depth of operation causes both the magnitude and the gradient of both linear distributions to change according to the variation of soil mechanical resistance with depth.

Figure 1. Main components of the instrumented deep-tillage implement.
A LabView (National Instruments Corporation, Austin, Texas) interface was developed to acquire the signal conditioned with a signal-conditioning accessory (SC–2043–SG) and processed by a 12–bit A/D converter (DAQCard–1200). The data acquisition card was sampled at approximately 120 Hz, and averages obtained every second were stored in a delimited text file. Known gauge factors and excitation voltage were used to calculate the strain as measured by each set of strain gauges. The installed load cells were calibrated in the laboratory using another pre–calibrated load cell with forces of up to 10 kN. To account for data acquisition system offset, every transducer was set to 0 with no load applied before each pass through the field.

An ultrasonic distance sensor (UNAM 30U9103, Baumer Electric AG, Frauenfeld, Switzerland) was used to measure tillage depth. Depth measurements were verified manually during preliminary field trials described later. Operating depth ranged from 0 to 60 cm. Geographic position (longitude and latitude) as well as true travel speed were determined with a GPS receiver (beacon differential correction). Measurements obtained by the instrumented deep–tillage implement were analyzed using theoretically derived mathematical expressions, and calculated parameters were associated with average soil profiles obtained from a set of soil cone penetrometer measurements (“The Investigator” compaction meter, Spectrum Technologies, Inc., Plainfield, Ill.).

**ANALYTICAL METHOD (FULL SOLUTION)**

Free body diagrams of both the shin and the standard–point assembly are shown in figure 3. It is assumed that the front edge of the standard is perpendicular to the soil surface during operation. In the current design, load cell 1 is installed at the same level as the top of the point. Soil resistance applied to the shin was represented by a linear distribution of soil resistance pressure \( p_{sh} \). The distance between the soil surface and load cell 1 is variable and depends on tillage depth. Similarly, soil resistance applied to the point was represented by linear distribution \( p_{pp} \). Since both distributions can be characterized by two parameters, a total of four measurements are required.

The free body diagram of the shin (fig. 3a) was used to derive \( p_{sh} = f(y) \), where \( y \) is a vertical coordinate with respect to the tip of the point. Similarly, \( z \) is a vertical coordinate with respect to load cell 1 (top of the point). All transducers were numbered from point up: load cell 1, strain gauges 2, load cell 3, and strain gauges 4.

The magnitude and position of resultant resistance force \( R_{sh} \) can be defined as:

\[
R_{sh} = F_1 + F_3
\]

\[
Z_{Rsh} = \frac{F_3 Z_3}{R_{sh}}
\]

where

\( R_{sh} = \) total resistance force acting on the shin (N)
\( F_1 = \) load cell 1 measurement (N)
\( F_3 = \) load cell 3 measurement (N)
\( Z_{Rsh} = \) \( z \) coordinate of the resultant force \( R_{sh} \) (mm)
\( Z_3 = \) \( z \) coordinate of load cell 3 (mm).

Both \( R_{sh} \) and \( Z_{Rsh} \) can be used to define the two values of the linear pressure distribution:

\[
P_{sh} = \frac{2 R_{sh}}{b_{sh} Z_s} \left( \frac{3 Z_{Rsh}}{Z_s} - 1 \right)
\]

\[
P_{sh1} = \frac{2 R_{sh}}{b_{sh} Z_s} \left( 2 - 3 \frac{Z_{Rsh}}{Z_s} \right)
\]

where

\( p_{sh} = \) predicted value of soil resistance pressure at soil surface (MPa)
\( p_{sh1} = \) predicted value of soil resistance pressure at load cell 1 (MPa)
\( b_{sh} = \) frontal width of the shin (mm)
\( Z_s = \) \( z \) coordinate of soil surface (mm).

Since \( y = z + Y_1 \), \( p_{sh} = f(y) \) can be defined as:

\[
p_{sh}(y) = p_{sh1} + \frac{p_{sh} - p_{sh1}}{Y_s - Y_1} (y - Y_1)
\]

where

\( Y_1 = \) \( y \) coordinate of load cell 1 (mm)
\( Y_s = \) \( y \) coordinate of soil surface (mm).
Similarly, the free body diagram of the standard and point assembly (fig. 3b) can be used to derive $P_p = f(y)$. Two new coordinates ($x$ and $l$) were added. Coordinate $x$ represents the horizontal distance with respect to the front of the shin. Coordinate $l$ represents the distance along the front surface of the point with respect to its upper end ($l = 0$ if both $x = 0$ and $z = 0$).

Both sets of strain gauges were used to calculate the bending moment at the corresponding cross-sections:

$$M_2 = \frac{1}{6} E h_2^2 \kappa_2 \times 10^{-6}$$

$$M_4 = \frac{1}{6} E h_4^2 \kappa_4 \times 10^{-6}$$

where \(M_2, M_4\) = bending moment at locations of strain gauges 2 and 4 (N mm) \(E\) = modulus of elasticity (2.07 \times 10^5 MPa for steel) \(h_2, h_4\) = cross-section length of the standard (mm) \(\kappa_2, \kappa_4\) = strains measured by strain gauges 2 and 4 (\mu m/m).

The magnitude and location of the resultant resistance force ($R_p$) can be defined as:

$$R_p = \frac{A_2 - A_4}{B_2 - B_4}$$

$$L_{R_p} = \frac{A_4 B_2 - A_2 B_4}{A_2 - A_4}$$

where $R_p$ = total resistance force applied to the point (N) $L_{R_p}$ = $l$ coordinate of the resultant force $R_p$ (mm) $A_2, A_4$ = bending moment of force $R_p$ sensed by strain gauges 2 and 4 (N mm) $B_2, B_4$ = geometry parameters (mm).

$$A_2 = M_2 - F_1 Z_2$$

$$B_2 = Z_2 \sin \alpha + X_2 \cos \alpha$$

$$A_4 = M_4 - F_4 Z_4 - F_3 (Z_4 - Z_3)$$

$$B_4 = Z_4 \sin \alpha + X_4 \cos \alpha$$

where $Z_1, Z_2, Z_3, Z_4$ = $z$ coordinates of corresponding transducers (mm) $X_2, X_4$ = absolute values of $x$ coordinates for the cross-section center at strain gauges 2 and 4 (calculated based on $h_2$ and $h_4$; mm) \(\alpha\) = slope of the point:

$$\tan \alpha = \frac{Y_1}{X_0}$$

Both $R_p$ and $L_{R_p}$ can be used to define two values of the linear pressure distribution:

$$p_{R_p} = \frac{2 R_p}{b_p L_0} \left(3 \frac{L_{R_p}}{L_0} - 1\right)$$
where

\[ L_0 = \text{total length of the front of the point (mm)} \]
\[ b_p = \text{frontal width of the point (mm)} \]

Using these parameters, \( p_p = f(y) \) can be defined as:

\[ p_p(y) = p_{p0} + \frac{p_{p1} - p_{p0}}{Y_1} y \]  

(17)

To compare both predicted \( p_{sh} \) and estimated \( p_p \) resistance pressure applied to the point, the \( y = Y_{Rp} \) coordinate can be used:

\[ Y_{Rp} = Y_1 - L_{Rp} \sin \alpha \]  

(18)

**REDUNDANT SOLUTION**

Although defining both distributions \( p_{sh} \) and \( p_p \) is feasible using four transducers, inaccurate measurements can significantly change the slopes of both distributions. As a partial case of the full model, a redundant solution was used during preliminary field testing. It included two simplifications:

1. Set \( p_{sh} \) to 0 while assuming no mechanical resistance at the surface. In this case, equation 4 can be substituted with:

\[ p_{sh} = \frac{2R_{sh}}{b_{sh}Z_s} \]  

(19)

2. Assume \( p_{p0} \) equal to \( p_{p1} \) and define \( R_p \) using averages from two sets of strain gauges:

\[ R_p = \frac{1}{2} \left( \frac{A_2}{L_{Rp} + B_2} + \frac{A_3}{L_{Rp} + B_4} \right) \]  

(20)

In this case, \( L_{Rp} = L_0/2 \), and equations 15 and 16 can be combined as:

\[ p_{p0} = p_{p1} = \frac{R_p}{b_pL_0} \]  

(21)

**FIELD EVALUATION**

Field testing of the instrumented deep−tillage implement was performed in two soil conditions. Both plots were assumed to have relatively small spatial variance of soil mechanical resistance, moisture, and other properties. The first test location was a non−agricultural compacted area (test track) with a definite increase in soil resistance between 15 and 30 cm superimposed on top of a linear distribution (as shown by cone penetrometer measurements). The second location was a part of a no−till field with silty clay loam soil, almost linear change in soil resistance with depth, and a relatively low level of compaction.

Seven and eleven cone index measurements were obtained at each of the two locations, respectively (fig. 4). The instrumented deep−tillage implement was operated while traveling below 1 km/h in several (3 to 4) short passes at least 2 m apart. While continuously logging data, three operating depths were maintained for at least 10 consecutive seconds during each pass. Equations 5 and 17 with corresponding simplifications of the redundant solution were used to calculate predicted and measured soil mechanical resistance, respectively, at the point.

**RESULTS AND DISCUSSION**

Figure 5 indicates the soil mechanical resistance pressure predicted, \( p_{sh}(Y_{Rp}) \), from the linear pressure distribution applied to the shin and measured, \( p_p(Y_{Rp}) \), at the point for 40 s portions of a single pass from each test location. According to figure 5a, data collected from the first test location indicates a large change in the difference between \( p_{sh}(Y_{Rp}) \) and \( p_p(Y_{Rp}) \) when operating at different depths. At the second location (fig. 5b), on the other hand, the measured soil mechanical resistance pressure applied to the point was greater than predicted at every operation depth \( (p_p > p_{sh}) \). This suggests that the first test plot has greater deviation from the linear change of soil mechanical resistance with depth compared to the second plot.

Figure 6 illustrates the soil mechanical resistance profile defined as averages of cone index measurements in 5 cm increments, as well as those expressed by \( p_{sh} \) and \( p_p \). Points used to generate these graphs are identified in figure 5 as: point A (5 s, first plot), point B (20 s, first plot), point C (10 s, second plot), and point D (35 s, second plot). Circles in figure 6 represent values of the \( p_{sh}(y) \) distribution calculated at \( Y_s \), \( Y_{sh} \), \( Y_1 \), and \( Y_{Rp} \) (predicted), while squares show values of the \( p_p(y) \) at \( Y_1 \), \( Y_{Rp} \) (measured), and \( Y_0 \).
Figure 5. Travel pass through (a) first (compacted) test plot, and (b) second (no− till) test plot. Predicted resistance, $p_{sh}(Y_{Rp})$, was determined using equation 5, while measured resistance, $p_{sp}(Y_{Rp})$, was determined using equation 17. Parameter $Y_{Rp}$ was defined using equation 18.

Figure 6a indicates that soil mechanical resistance measured at the implement’s point at point B was lower compared to the resistance predicted from the load applied to the shin. This suggests that the soil displaced by the point had lower mechanical resistance than the soil displaced by the lower portion of the shin. However, this difference becomes insignificant when increasing the depth of operation (point A) because of the secondary layer with high soil mechanical resistance, as was discovered from the cone penetrometer measurements. Figure 6b, on the other hand shows that despite the operation depth (points C and D), the measured soil resistance was always higher than predicted for the selected test area.

According to figure 4, cone index measurements performed in both test plots indicated high variability at a given depth, with coefficients of variability (CV) reaching 79% at the surface and 26% below 30 cm. Such variability is primarily caused by the fact that cone index measurements were performed at locations that may have differences even when obtained from an area with relatively homogeneous soil conditions. Part of this variability was observed by the instrumented deep−tillage implement while operated at a constant depth (CV generally less than 20%). The difference of absolute values obtained with the soil cone penetrometer and instrumented implement measurements can be explained by the nature of both instruments (vertical penetration versus horizontal tillage). Therefore, cone index measurements could be used only as indicators of depth variability of soil mechanical resistance, and not for direct validation of the instrumented deep−tillage implement.

In addition, both plots did not have a well−defined hardpan without significant increase of soil mechanical resistance below 40 cm. This suggests that the utilization of the instrumented deep−tillage implement would be limited in the conditions tested. Neither of the alternative test locations in Nebraska had cone penetrometer measurements indicating significant variability of the depth of a well−defined compacted soil layer in a single field, although such conditions have been documented in other regions (Gorucu et al., 2003). Therefore, alternative testing of the developed instrumented deep−tillage implements is needed prior to the development of a variable−depth tillage control algorithm. After such an algorithm is developed, the instrumented deep−tillage implement could provide supplemental inputs for a real−time closed−loop depth control system, as shown in figure 7. Field evaluation of such a system will require a
number of trials studying both agronomic and economic impacts in various geographic areas.

CONCLUSION
A prototype instrumented deep–tillage implement was developed to estimate parameters of linear soil resistance pressure distributions acting on the protective shin (psh) and the point (pp). Both distributions can be extended to overlap and allow comparison of predicted and measured soil resistance. A significant deviation of the true distribution from a steady linear model (such as the deviation produced by the presence of a compacted layer) will cause disagreement between psh and pp estimated at the same depth. The absolute value of soil resistance pressure can be used to determine whether tillage of the particular area is appropriate. Limited field evaluation has shown the ability of the system to sense nonlinear vertical distributions of soil mechanical resistance while operating at varying depths. However, additional studies are needed to develop the algorithm for closed–loop control during real–time variable–depth tillage.

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