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**DEVELOPMENT OF AN INSTRUMENTED SUBSOILER
TO MAP SOIL HARD-PANS
AND REAL-TIME CONTROL OF SUBSOILER DEPTH**

By

G. Manor
Associate Professor
Agricultural Engineering Dept.
Technion, IIT
Haifa Israel
agmanor@tx.technion.ac.il

Rex L. Clark
Professor
Bio. & Agr. Eng. Dept.
University of Georgia
Athens Georgia USA
rclark@engr.uga.edu

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Abstract: An instrumented subsoiler shank was designed and built to measure the soil resistance while moving through the soil and for automatic control of the depth of several standard subsoiler shanks mounted on the same frame. Three load cells measure the resultant magnitude and direction of the soil reactions on the shank. Two load cells measure forces perpendicular to the straight shank with a constant distance between them and another load cell measures the force along the shank. The two perpendicular load cells are cantilevers with one side mounted to the center of the shank's width and the other side connected to wheels running inside a hollow beam. The wheels enable the shank to be moved up and down for different depths with the aid of a hydraulic cylinder. The hydraulic cylinder is connected to the upper edge of the shank by the lengthwise load cell. The resultant force on the shank is calculated by using the three measured forces, their directions and locations. The instrumented shank was calibrated and tested in the field. While preliminary in nature, the results indicate that when the shank tip is above a soil hardpan, the soil force on the tip acts upward, and becomes negative when the shank tip is below the hardpan. These results indicate that it may be possible to determine the depth of the hardpan by observing when the vertical force on the shank tip passes through zero as the shank depth is cycled above and below the hardpan.

Keywords: Subsoiler, Soil Resistance Mapping, Depth Control, Hard-pan.

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Introduction

Compacted soil, particularly compacted hard-pans, are well known to significantly decrease crop yield (Taylor, 1990; Hakensson, 1988). Therefore mapping techniques to produce soil strength maps, which can be related to yield maps, is important for precision tillage operations. The soil strength maps and particularly hard-pan maps may be generated as frequently as necessary and included in a precision farming geographic information system (GIS).

It is well known that soil hard-pans restrict crop root growth, particularly into the sub-soil, thereby limiting root access to nutrients and moisture in the subsoil. These hard-pans are created by traffic and tillage operations as well as by natural forces. They reduce yields, slow water infiltration, cause soil erosion, limit productivity, accumulate lower amounts of water and make plant susceptible to temporal drought stress. It is thought that most upland sandy soils of the coastal plains in the Southeastern U.S., as well as many soils around the globe have a hard-pan at about 15 to 36 cm deep and 5 to 15 cm thick (Clark et al, 2000; Radcliffe et al., 1989; Taylor, 1963; 1990). This hard-pan must be broken so that the crop root can grow into the subsoil for top crop performance.

Farmers attempt to break the hard-pan with annual subsoiling, usually to a uniform depth in the 25-50 cm range. However, farmers do not usually know if annual subsoiling is required, where it is required in a field, and at what depth. Clark et al (1993) determined that subsoiling needs to be conducted annually on severely eroded soils. Farmers in Israel are breaking hard pans with subsoilers annually at a depth range of 35 to 50 cm. Initial studies by Raper et al (2000a; 2000b) and Clark (1994; 2000) have shown that the depth of the hard-pan and its strength, varies greatly from field to field and also within the same field, both horizontally and vertically in very short distances. Hadas (1988) found that the spatial variability of all soil parameters is also very large. Knowledge about the variation of the depth and existence of the hard-pan will help to determine if application of a uniform tillage depth is the most effective method of soil compaction amelioration, or if a depth controlled tillage may be beneficial. Raper (1999b) estimated that the energy cost of subsoiling could be decreased by as much as 34% with site-specific tillage as compared to the uniform-depth tillage technique currently employed by farmers. Cotton yields have also been shown to improve by as much as 10% when tillage depth is being controlled to the depth of the hard pan (Raper et al., 2000a) as compared to plowing to excessive depths in Tennessee Valley soils.

Measurement of soil strength at different depths has traditionally been conducted with the soil cone penetrometer (ASAE, 1998). The penetrometer has been used effectively as a tool to map soil hardpans (Clark & Reid, 1984; Manor et al., 1991; Radcliffe et al., 1989; Raper, et al., 1999a; Raper, et al., 2000a; Smith et al., 1978), although it requires a stop-and-go procedure that is time-consuming and costly. Several researchers have developed on-the-go instrumented tines which also promise as tools which can be used to map soil hard pans (Alihamshay et al., 1990; Bergeijk et al., 1996; Glancey et al., 1988; Hall et al., 2000; Stafford and Hendrick, 1985).

The objectives of the work described herein were to develop an instrumented subsoiler shank for measuring the soil resistance, at different depths, while moving through the soil and for automatic control of the depth of several standard subsoiler shanks mounted on the same frame.

Hardware and software development

The overall design criteria were:

1. To measure the forces acting on the measuring subsoiler shank with its chisel, their horizontal and vertical components, and the acting point on the shank.
2. To continuously control the depth, manually or automatically down to .50m.
3. To measure the chisel depth and record it into a GIS program.
4. To measure the geographical location of the chisel and record it into a GIS program.
5. To create a topographic map of the soil strength.
6. To be able to control the optimal depth of several subsoiler shanks in real time to break the measured had-pan.

The hardware was designed to follow the design criteria (Fig. 1). A photograph of the shank mounted on a toolbar is shown in Figure 7. The shank (2) can move inside the rails (1) with the aid of an upper set of wheels (3) and a lower set of wheels (4). A hydraulic actuator (18) is connected to the shank in order to change the depth on-the-go. The hydraulic actuator (18) is connected to the shank (2) via a load transducer (17). The load cell is an Entran Model ELHM-T4M-5KL 5000 pound tension/compression strain gage load cell. In parallel to the hydraulic actuator there is a linear potentiometer (R) to measure the depth of the chisel.

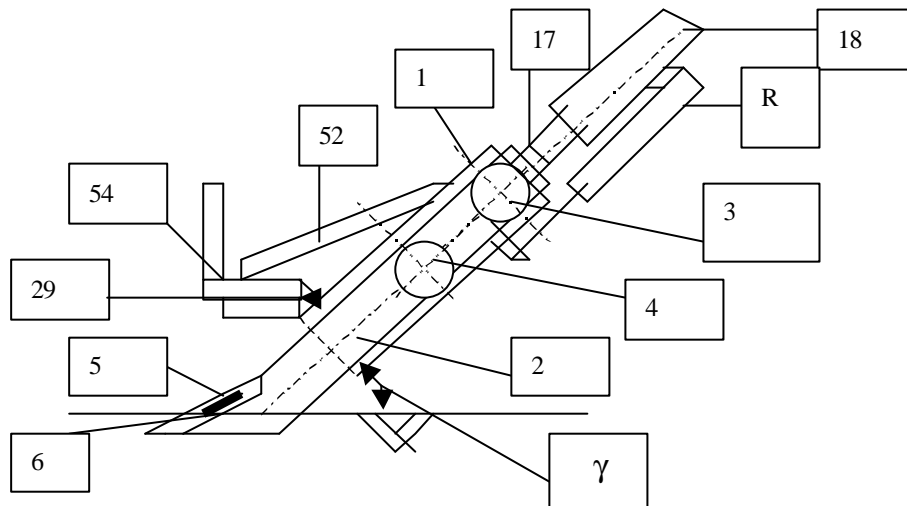


Figure 1. Measuring subsoiler – general view

Each set of wheels is mounted on a cantilever beam (13, 14) (Fig. 2) with strain gages to measure the force acting on it, normal to the shank.

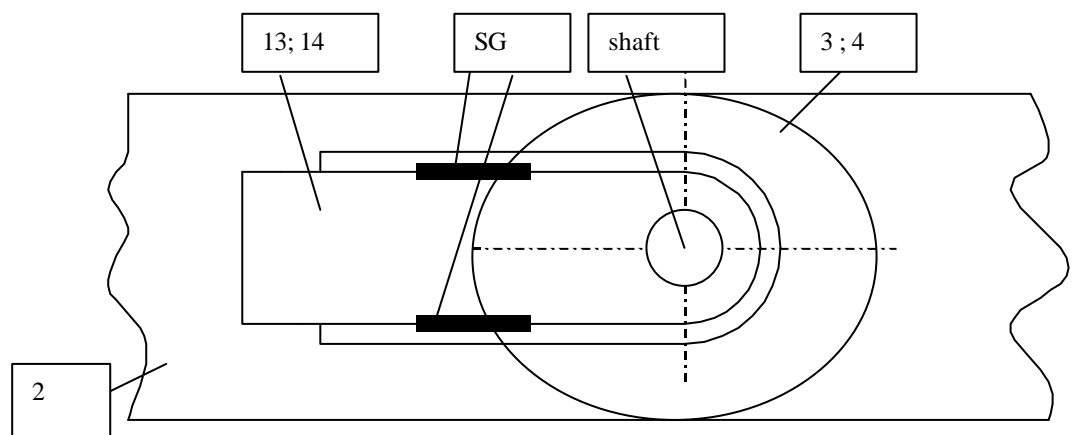


Figure 2. A wheel mounted on a cantilever beam by a shaft and bearings

The rails are mounted to a tool bar (54) by a hinge (29) and a link (52). By changing the length of the link, the vertical angle of the shank could be changed. This can help to determine the optimal angle at the developing stage.

The chisel (5) is mounted at the front end of the shank. The chisel can be changed to determine its optimal dimensions at the developing stage. It also can be mounted via a load cell (6) as the one developed by Stafford and Hendrick (1985), to measure the load on the chisel itself.

The depth control hydraulic system (Fig. 3) can be operated manually or automatically.

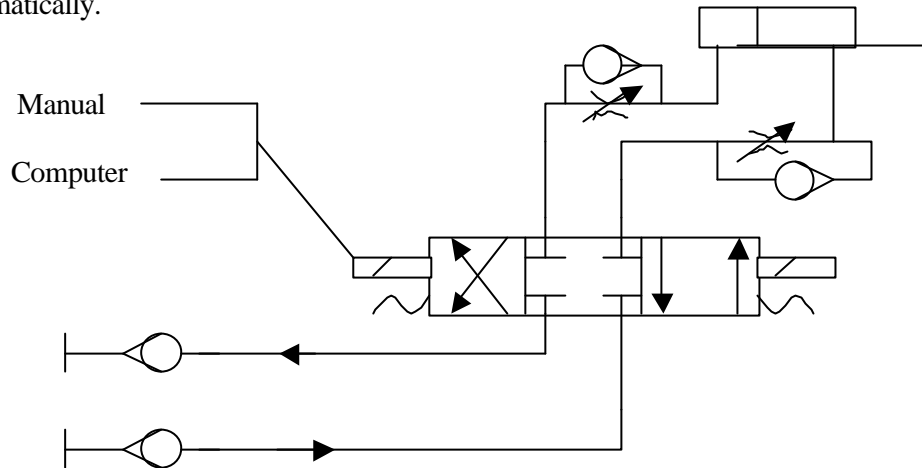


Figure 3. Depth control system

The measuring subsoiler was calibrated by loading the edge of the shank (Fig. 4) via a load transducer (F) perpendicular to the shank, measuring the resulting electric signals from the strain gages and correlate them to the computed forces (Equation 1 & 2).

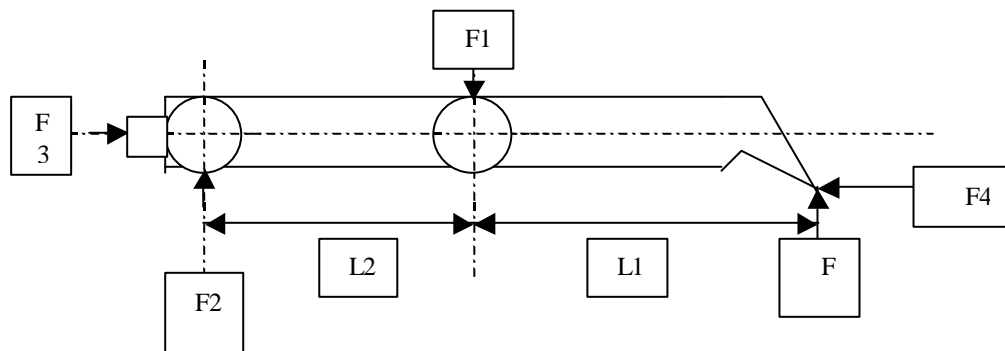


Figure 4. Calibrating procedure.

1. $F_1 = F(L_1 + L_2) / L_2$
2. $F_2 = F_1 - F$

The load cell (F3) was calibrated by the manufacturer and was used to measure the perpendicular load on the shank edge (F).

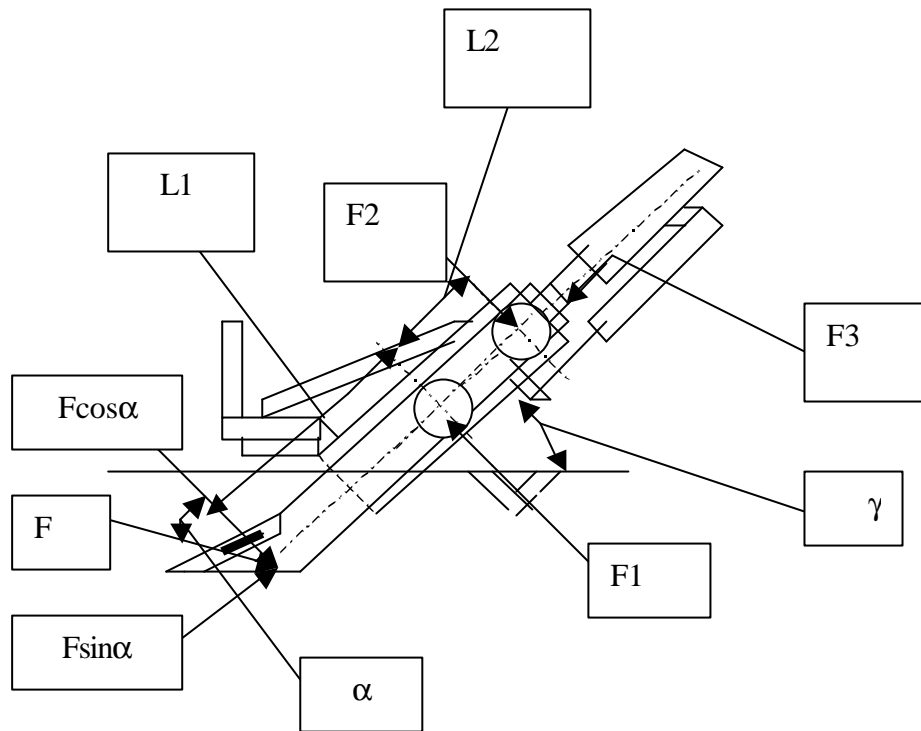


Figure 5. Calculation of the resultant force F on the shank.

Force calculation

3. $F \sin \alpha = F_3$
4. $F \cos \alpha = F_1 - F_2$
5. $L_1' = F_2 * L_2 / F \cos \alpha$
6. $F = \sqrt{(F \sin \alpha)^2 + (F \cos \alpha)^2}$
7. $\alpha = \text{arctg } F_3 / (F_1 - F_2)$

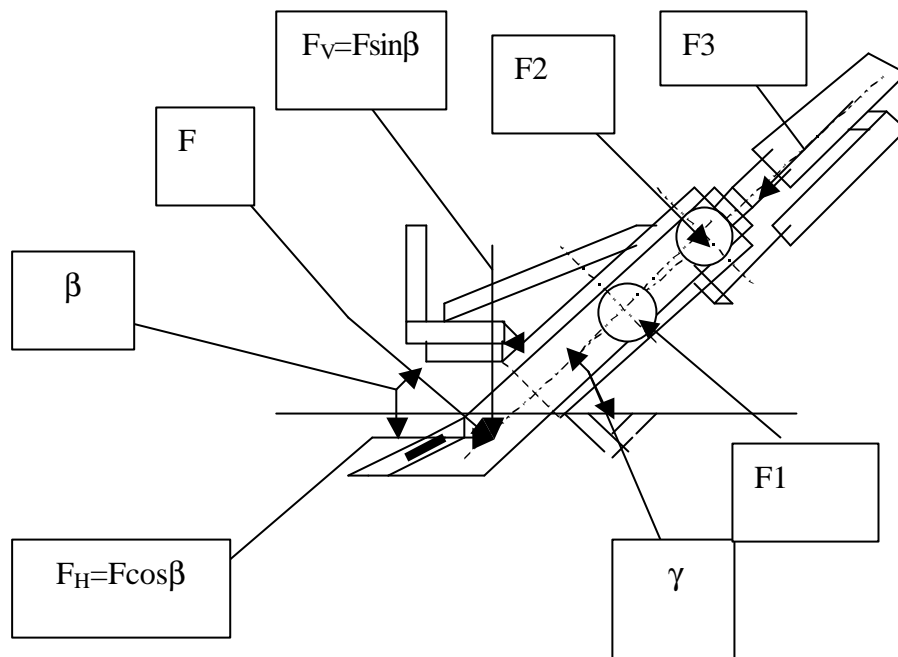


Figure 6. Calculation of the components of force F on the shank

8. $F_v = F \sin \beta$ vertical component
9. $F_h = F \cos \beta$ pull component
10. $\beta = 90 - \alpha - \gamma$ angle of the resultant force above the horizon

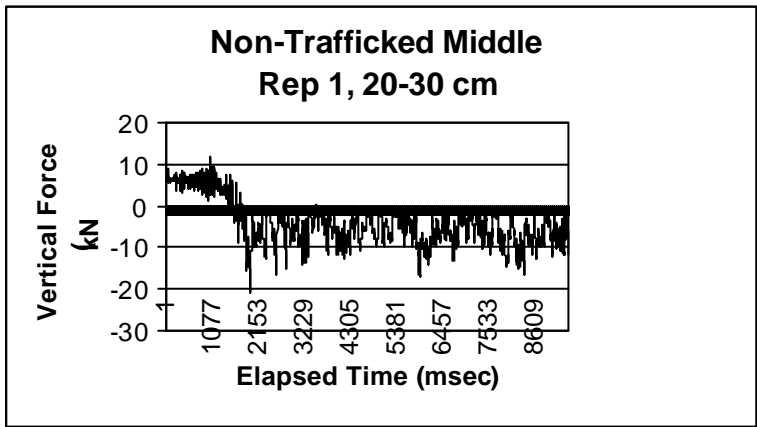
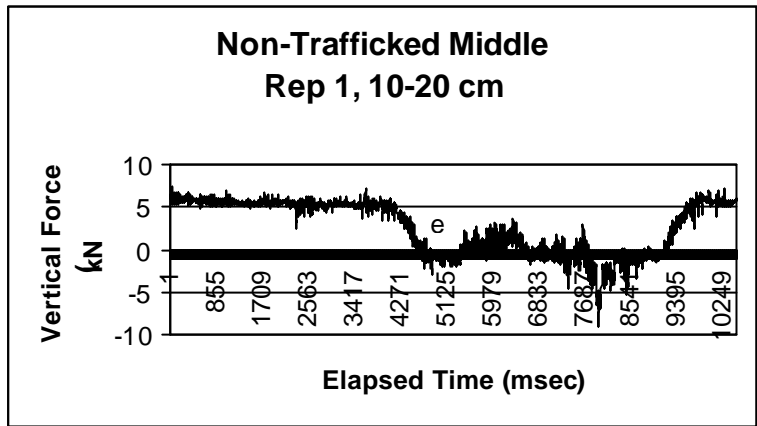
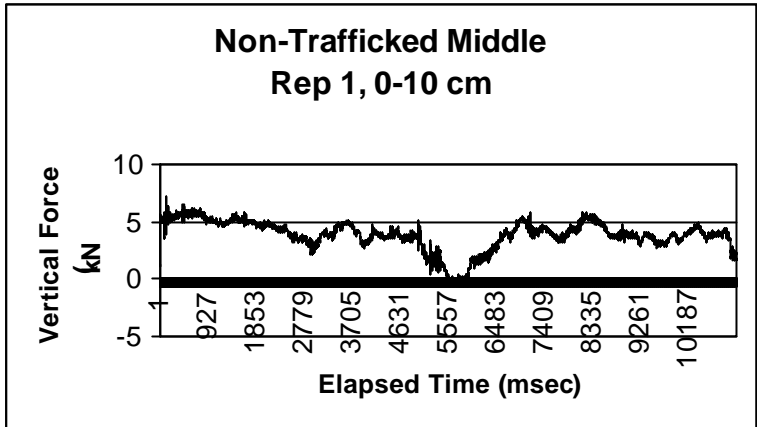


Figure 9. Vertical force for non-trafficked middle

PROCEDURES

Beginning in the Fall of 1991, and concluding in the Fall of 1996, an experiment was conducted at the Southern Piedmont Conservation Research Center, Watkinsville, GA to test the effect of controlled traffic and four tillage systems with a double crop system. The soil was a slightly croded Cecil sandy loam (clayey, kaolinitic, thermic, Typic Kanhapludult). The experimental plots including no-till planting with varying frequency of tillage, including tillage every year, every other year, every three years, etc. During these experiments, controlled traffic was carefully maintained on the plots so that the location of traffic and tillage operations remained the same year after year. Following the last experiments in Fall, 1996, the plots were not used for row crop production; they were mowed during the summer season to control weeds and grass. Each plot was 75' long and 10' wide. The row spacing used was 30"; the tractor wheel spacing used was 60", and 4 crop rows were planted in each plot.

It was possible to flag the location of the plot corners used during the experiments between 1991 and 1996 by using buried metal markers and GPS location (Leica SR9500 GPS sensor, 1996) for the markers. 6 plots were chosen in 2001 for these experiments which were conducted with 2 replicates. In one pair of plots, the location of one non-trafficked middle was identified with flags; in a second pair of plots, the location of one crop row was identified with flags; and in a third pair of plots, the location of one trafficked middle was identified. It was assumed that there would be differences in the depth and strength of soil hardpans in the plots as a function of the location of tillage and traffic operations.

Each of the sensors - the two strain gage sensors on the shank support shaft, the load cell, and the linear potentiometer, were first calibrated in the laboratory. Each sensor was connected to an IOTech WaveBook/512 signal conditioning system, which in turn was connected to a Gateway Model 2000 Solo notebook computer. The software used for data collection and analysis was DasyLab (IOTech, 1997) software designed specifically for this system. The software was set to collect and record data from all four sensors at the rate of 200 hz.

The toolbar which supported the sensor shank was mounted on the tractor three-point hitch, and had depth control wheels. A John Deere Model 4030 tractor was used to pull the shank sensor system. The tractor, toolbar, and shank were first placed on a flat surface and the depth control wheels were adjusted so that the shank tip was near the surface. The data collection software was written so that the potentiometer would give the depth of the subsoiler tip if the toolbar depth control wheels were on the ground surface.

To start data collection for a plot, the tractor was positioned at the end of the plot so that the sensor would either track through a non-trafficked middle, a crop row, or a trafficked middle. The front wheels of the tractor were positioned at the end of a plot. The three point hitch was positioned so that the depth control wheels were on the soil surface. When the tractor started moving, data collection was started and the subsoil shank was moved into the soil with the cylinder on the end of the shank until the potentiometer gave the desired depth. The first depth used was 10 cm. After completing the first pass, the tractor returned to the plot starting position and the experiment was repeated for a depth of 20 cm. A third pass through the plot was conducted at a depth of 30 cm. A second plot was used to run the subsoiler shank through the crop row location; a third plot was used to run the subsoiler shank through a trafficked middle. Data was then collected on replicate plots.

RESULTS AND DISCUSSION

The data will be presented in this paper in graphical form with discussion, but without a statistical analysis. Figure 8 presents the graphical results showing the horizontal force on the tip of the subsoiler shank for the non-trafficked middle. Since the tip of the shank was operated at depths of 10, 20 and 30 cm, it is considered that the sensor was actually measuring the soil force for the approximate depth ranges of 0-10, 10-20, and 20-30 cm. The results shown in Figure 8 are typical for all the plots. The horizontal force for the 0-10 cm depth

range usually ranged between about 1 and 6-8 kN and the change in force was nearly as dynamic as the change in force for the 20-30 cm depth range. For the 20-30 cm depth range, the horizontal force ranged from about 1- 12 kN. During the first half of the plot, the force dynamics were relatively smooth, but became dynamic during the second half of the plot. For the 20-30 cm depth range, the range of horizontal force was significantly higher (about 5 - 18 kN), and the dynamics of the data was much more noticeable.

Upon visual observation of the ground surface after each pass, it was noticed that after the last pass at the 30 cm depth, there would usually be large soil clods in the subsoiler slot near or on the surface. These clods did not usually appear when the sensor tip was at the 10 cm depth, and some clods would appear at the 20 cm depth. While not proven, it is believed that these clods were large pieces broken out of the soil hardpan.

The vertical force results shown in Figure 9 perhaps provide the most significant information. It can be seen that the vertical force for the 0-10 cm depth range had relatively low dynamic changes and ranged from 0 to about 6 kN. For the 10-20 cm depth range, the vertical force was relatively smooth for the first half of the plot with a mean value of 5-6 kN, but decreased to range about 0 for most of the second half of the plot. The data dynamics also increased as the subsoiler passed through the second half of the plot. For the 20-30 cm depth range, it can be seen that the vertical force was initially positive, then became and remained negative.

To provide an explanation of these results, it is important to understand that when the vertical force is positive, the soil force acting on the tip is upward; when the vertical force is negative, the soil force acting on the tip is downward. The following is one explanation of these results. It should be understood by the reader that this explanation is based on minimal data, and therefore this explanation needs further proof. For the 20-30 cm depth range, it is important to note that for some time period after the tractor started moving, the tractor moved some distance before the subsoiler shank tip had penetrated to 30 cm. During this time, it appears that the force on the tip was acting upward (positive). Then, when the tip was down to 30 cm, the force on the tip was acting downward (negative). While not proven, it is believed that this can be explained by considering that when the tip was at 30 cm, the hardpan was above the tip, and that the hardpan soil had a higher strength than the soil below the tip, giving a net downward force on the tip. Further, the fact that the vertical force ranged around 0 for the second half of the plot at the 10-20 cm depth range indicates that the tip was above the hardpan for the first half of the plot, and perhaps in or slightly below the hardpan for the second half of the plot. The fact that there was a short distance in the middle of the plot for the 0-10 cm depth range in which the vertical force was at or near zero indicates that the tip was just at the depth for this section of the plot. While the data presented in Figures 8 and 9 is only for one replication, the graphical data for the second replication is similar in nature, and apparently can be explained in a similar manner.

Assuming that this explanation of the results is correct, it can be seen that at the depth at which the vertical force passes through zero, this is probably the approximate depth of the hardpan. This implies that it may be possible to design a depth control system in which the hydraulic depth control system can "hunt" for the hardpan by cycling the shank tip depth around the point where the vertical force on the tip is zero.

These results are preliminary in nature and require further experiments to verify the hypothetical nature of our explanation of the results. It is expected that the type of results obtained were significantly influenced by the dryness of the hardpan which allowed the hardpan to be broken up into large clods, rather than for the subsoiler shank to simply slice through the hardpan. It would be expected that if the moisture content of the soil in the hardpan is sufficiently high, the subsoiler shank will likely slice through the hardpan and not create the soil clods, which may significantly influence the nature of the data from the sensor.

CONCLUSIONS

A hardpan sensor to measure the strength and depth of soil hardpans was developed using three strain gage and one potentiometric sensors. The sensor was designed to enable the measurement of both the horizontal and vertical force on the subsoiler tip, and the tip depth. The sensor was calibrated, mounted on a toolbar, and preliminary data was collected in a series of controlled traffic plots with known tillage histories.

While preliminary in nature, the results indicate that when the shank tip was above a soil hardpan, the soil force on the tip acted upward, and became negative when the shank tip was below the hardpan. These results indicate that it may be possible to determine the depth of a soil hardpan by observing when the vertical force on the shank tip passes through zero as the shank depth is cycled above and below the hardpan. While not examined or proven in this study, this result is likely a function of the moisture content of the soil, particularly the moisture content of the soil hardpan. Additional studies are needed in other soils and under additional soil moisture conditions to verify the implications of the results.

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