DEVELOPMENT AND CONCEPT EVALUATION OF AN ON-THE-GO SOIL STRENGTH MEASUREMENT SYSTEM

H. E. Hall, R. L. Raper

ABSTRACT. *Root-restricting soil layers reduce crop yields in the southeastern U.S. almost every year due to temporary periods of drought. Subsoiling beneath these layers is an annual practice for most farmers in this region as a method of removing this barrier and improving rooting conditions. Currently, farmers could use a soil cone penetrometer to determine the depth of their root-restrictive layer in a few locations within a field and then set their tillage depth to exceed the deepest root-restricting layer found. However, the potential for significant energy savings exists if some method of sensing the depth of this layer was available on-the-go and adjustments could in turn be made to subsoiling depth. A prototype design of an on-the-go soil strength sensor was developed as a possible alternative to the cone penetrometer and as a method of sensing the depth of the root-restricting layer. Several versions of this sensor were evaluated in a sandy loam soil bin at the USDA-ARS National Soil Dynamics Laboratory. The sensor was able to detect compacted soil profiles in a similar fashion as the cone penetrometer. The on-the-go soil strength measurements were more closely correlated to bulk density than the cone penetrometer measurements and exhibited less variation than cone penetrometer measurements. Further research with this sensor could lead to methods of quickly and easily mapping soil compaction within fields.*

Keywords. *Cone index, Sensors, Soil compaction, Soil moisture, Soil strength.*

Root-restricting soil layers reduce crop yields in the southeastern U.S. almost every year due to temporary periods of drought. Subsoiling beneath these layers is an annual practice for most farmers in this region as a method of removing this barrier and improving rooting conditions. One soil physical property modified by tillage to ameliorate root-restricting layers is soil strength. Research has shown that excessive values of soil strength can have detrimental effects on root growth and crop yield (Taylor and Gardner, 1963; Bowen, 1976). Subsoiling serves to reduce or alleviate problems of excessive soil strength within soils. Traditional methods of prescribing tillage treatments to the soil have been based on preventive maintenance, rather than diagnostic evidence. Researchers have recognized the inherent inefficiency of such tillage treatments and have proposed tillage systems where the soil prescribes the necessary tillage treatment to alleviate excessive soil strength problems. These systems would require determination of the soil strength to determine the depth of subsoiling needed (Bowen and Coble, 1967; Schafer et al., 1981).

The soil cone penetrometer (*ASAE Standards*, 2004b) has been traditionally used to assess the soil strength within a soil profile. The cone penetrometer measures the force required to insert a cone tip into the soil. Cone index is calculated by dividing this insertion force by the base area of the cone. Cone index is an empirical measurement of soil state and measures the net effect of several soil properties. The cone penetrometer is not a practical method to determine soil compaction in a large-scale field setting (Raper et al., 1999). A dense sampling scheme must be used if the true variation of soil compaction within a field is to be determined. Researchers have attempted to design sampling tools that can determine soil compaction fast enough to permit field-scale mapping of soil compaction (Raper et al., 1999). Limited success has been achieved in this endeavor to build a tool capable of rapid soil strength determination. The tools have only been able to determine soil strength at discrete depths (Alihamsyah and Humphries, 1991; Adamchuk et al., 2001). A system capable of rapid determination of soil strength throughout the soil profile has yet to be developed. A project was initiated to develop a soil strength sensor that could rapidly determine soil compaction throughout the soil profile. The on-the-go soil strength sensor (OSSS) developed for this research is similar in concept to a tool designed at North Carolina State University for horizontal determination of soil strength (Alihamsyah and Humphries, 1991).

The stop-and-go insertion method used in penetrometer data collection is not fast enough to obtain valid data in intensive sampling situations (Raper et al., 1999). Mulqueen et al. (1977) noted that cone index values are valid for comparison only when the measurements were taken under similar soil conditions. Researchers have developed intrusive methods for on-the-go impedance measuring (Young et al., 1988; Alihamsyah et al., 1990; Smith et al., 1994).

Attempts have been made to quantify soil conditions with draft (Young et al., 1988; Smith et al., 1994); however, draft alone is not a good indicator of soil conditions, because two soils may have the same mean draft, but have different

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physical conditions (Gill and Vanden Berg, 1968; Smith et al., 1994). Alihamsyah et al. (1990) developed and tested a horizontally operating blade with an impedance-sensing tip. This prototype tested two tip designs: a standard 30° cone, and a 30° wedge. Both tip designs were tested against a standard vertically operated cone penetrometer. The 30° wedge was found to most closely correlate to the standard cone penetrometer. In field tests, Alihamsyah and Humphries (1991) determined that the horizontal blade with a 30° wedge was most suitable for horizontal determination of soil strength. However, the study did not address the effects of tip size or tip position on soil strength measurements. Chukwu and Bowers (1997) developed a multiple-probe horizontal blade penetrometer with a 30° wedge for testing probes. This unit was able to detect impedance values at three distinct depths. Other similar designs for determining soil strength at several discrete depths are currently under development (Weissbach and Wilde, 1997; Adamchuk et al., 2001).

The limitation of previous horizontal penetrometer designs is that measurements are only taken at a finite number of depths. The development of the multiple-probe horizontal penetrometer is one step toward being able to completely determine a profile description of soil strength. An improved system could allow impedance to be measured continuously throughout the soil profile, as cone index data obtained in several southeastern U.S. fields indicate that the depth of the root-restricting layer is quite variable (Raper et al., 2001; Raper et al., 2005). Measurements of horizontal soil cone index at multiple depths can be obtained in either of two ways: by using multiple transducers at different discrete depths (Alihamsyah et al., 1990), or by using a single sensor and moving the probe vertically during operation.

Our approach has been to create a system to measure horizontal soil strength on-the-go by vertically oscillating the sensing element up and down as we move forward through the soil. This method has resulted in a U.S. patent (Raper and Hall, 2003). We feel that there are several advantages in this approach as compared to having multiple sensors per shank that do not move vertically. Hardpan profiles can be relatively thin in southeastern soils as evidenced by cone index data presented by Raper et al. (1994), which showed the hardpan profile in conventional tillage systems extending from an approximate depth of 0.25 to 0.35 m. Similar results were shown by research conducted in a different soil type where the hardpan depth was 0.1 to 0.2 m (Raper et al., 2000). Sensors that are placed too far apart or are not placed near the center of the hardpan profile could result in erroneous data. The oscillation speed of the patented system (Raper and Hall, 2003) could be adjusted to adequately determine soil strength variation depending on the soil's needs and would not miss the depth of the hardpan layer due to improper sensor placement.

A second advantage of the oscillating probe is that only one measurement of force is required, rather than several where the multiple-sensor shank is employed. Reduced instrumentation cost could partially compensate for the increased mechanical cost required to oscillate the probe.

The patented system (Raper and Hall, 2003) also has another advantage that may be more important than soil strength sensing. Other sensors could be combined with the single sensing tip and used to measure other parameters in the soil at all depths throughout the soil profile without the added cost of maintaining multiple sensors.

The objections of this research were to:

- Determine the optimal tip design of the force sensor for measurement of horizontal soil strength that would compare favorably with measurements of soil strength obtained vertically with a soil cone penetrometer.
- Determine the feasibility of measuring horizontal soil strength while vertically oscillating the shank as it moves forward through the soil.

METHODS AND MATERIALS

The on-the-go soil strength sensor (OSSS) is composed of three components: a sensing tip, a shank, and a force transducer. The OSSS shank was designed to provide a method of inserting the force transducer and the soil strength sensing tips into the soil (fig. 1). The OSSS shank was constructed from 37.5 × 150 mm A-36 plate steel, with a total shank length of 900 mm. The shank was designed to be pulled at a perpendicular rake angle to the soil surface. The shank was designed so that the sensor would have a maximum effective measuring depth of 600 mm and a shank width of 37.5 mm to protect the 36.5 mm wide force transducer.

To limit the formation of a soil wedge in front of the advancing shank, the leading edge of the shank was beveled to form a 30° prismatic wedge similar to the impedance sensing tips. This bevel should eliminate any soil from forming on the front of the shank and maintain consistent force values as the shank is pulled through the soil (Gill and Vanden Berg, 1968).

The OSSS shank was designed to penetrate vertically into the soil profile with minimum downward force. To facilitate this penetration into the soil profile, the bottom of the shank was cut on a 45° angle and beveled to a 30° prismatic wedge.

A 30 mm tall × 50 mm deep section was removed from the front of the shank to position the sensing tip flush with the

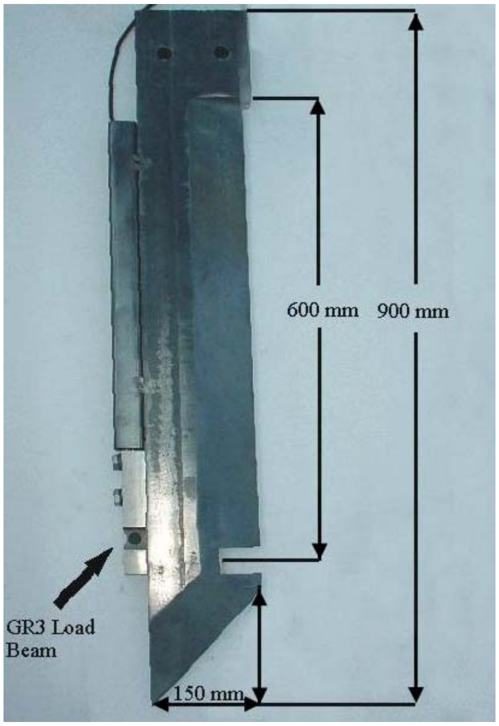

Figure 1. OSSS shank without sensing tips.

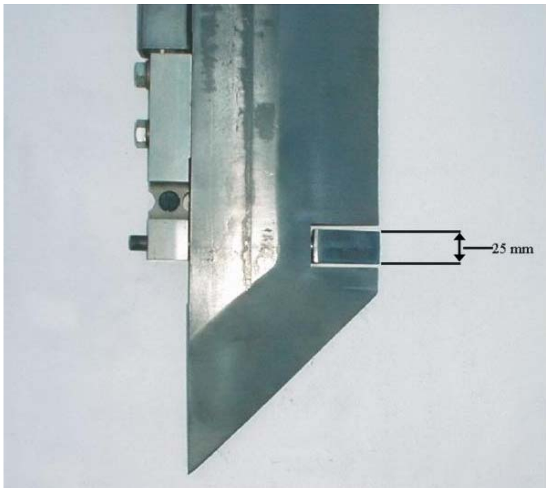

Figure 2. OSSS with the flush-mounted 625 mm^2 impedance sensing tip (ST1).

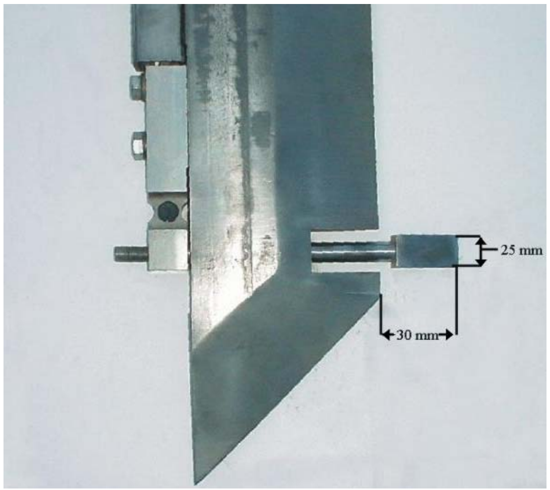

Figure 3. OSSS with the extended 625 mm^2 impedance sensing tip (ST2).

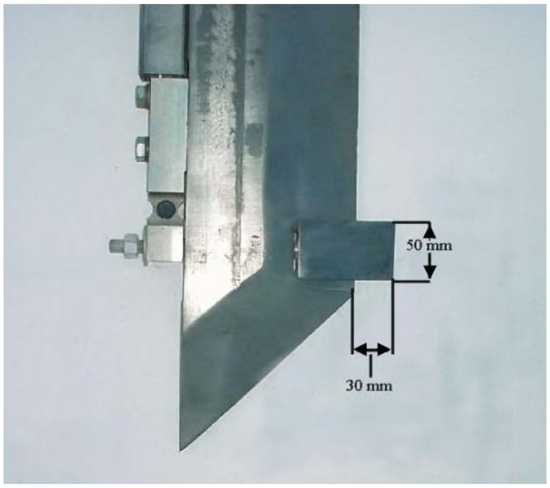

Figure 4. OSSS with the 2500 mm^2 impedance sensing tip (ST3).

leading edge of the shank. A 20 mm hole was drilled through the center of the removed section to allow the impedance tip to pass through the shank unobstructed and connect to the force transducer placed on the back of the shank. A square tube cable protector (37.5 × 6.4 mm wall thickness) was welded to the rear of the shank to prevent damage to the force transducer cable.

The force transducer chosen for the OSSS was a SENSOTEC GR3 load beam (SENSOTEC, Columbus, Ohio), with a 4.45 kN measurement capacity. The transducer capacity was selected to accommodate the range of forces expected from the selected tip sizes. The GR3 load beam is a cantilever beam design, capable of measuring tensile and compressive loads.

Three 30° prismatic wedge tips were designed and tested with the OSSS unit based on research conducted by Alihamsyah and Humphries (1991). The original tip designs were formed from 25 mm bar stock (figs. 2 and 3). The tips produced from the 25 mm bar stock have a cross-sectional base area of 625 mm^2 and were built in two lengths. Sensing tip 1 (ST1) was flush with the leading edge of the shank, to allow vertical movement through the soil profile without adding vertical forces to the shank (fig. 2). Sensing tip 2 (ST2) protruded 30 mm in front of the advancing shank (fig. 3). This protruding tip was built to determine if the position of the tip affected horizontal soil strength measurements obtained with the OSSS unit. The impedance tips were connected to the force transducer by a 16 mm beam, which passed through an oversized hole drilled in the shank.

In tests at the USDA-ARS National Soil Dynamics Laboratory (NSDL) with ST1, insufficient levels of horizontal soil strength measurements with the tip/load cell combination were encountered in several soil conditions. To remedy this problem, a third impedance sensing tip was created with a 2500 mm^2 cross-sectional base area, which was built from 50 mm bar stock (fig. 4). Sensing tip 3 (ST3) protruded 30 mm in front of the leading edge of the shank. Material was removed from the top and bottom of ST3 to allow the tip to recess in the slot in the shank that was cut for ST1 and ST2.

Data acquisition was accomplished with a Modcomp data acquisition system. For tests with the soil strength sensor, the system was set to sample the force transducer at 25 Hz. The force transducer was calibrated to the Modcomp system using a 4.45 kN tension or compression proving ring (Morehouse Instrument Company, York, Pa.).

Horizontal and vertical dynamic movement of the OSSS unit was accomplished with the dynamometer soil bin car. This car had the capability to move a tillage tool upward or downward in the soil as the car traversed the soil bin at a constant speed of 0.45 m s^{-1}. Depth was recorded by a depth recording motor (Celseco Transducer Products, Inc., Canoga Park, Cal.) during testing.

Evaluation of the OSSS was conducted in the Norfolk sandy loam (fine-loamy, siliceous, thermic Typic Paleudults) indoor soil bin at the USDA-ARS-NSDL. The Norfolk sandy loam soil bin is 7 m wide, 58 m long, and 1.5 m deep, with a particle size distribution of 71.6% sand, 17.4% silt, and 11% clay. The soil is uniform in mechanical composition, i.e., natural profiles were not reproduced in the bin. The indoor soil bin was selected because moisture content within the soil was controllable in this environment and this soil type is conducive to hardpan formation.

A series of four experiments were conducted with the OSSS. The first three experiments were designed to assess the different tip designs and their ability to determine horizontal soil strength at static depth positions. A uniformly dense soil condition was produced for the first three experiments with the OSSS unit. This soil condition was created by rotary tilling the soil to a depth of 450 mm and then packing the soil with a rigid wheel at a depth of 300 mm. The soil was then rotary tilled above the 300 mm depth and a second packing with the rigid wheel conducted at a depth of 150 mm. The soil was then rotary tilled above the 150 mm depth and shallow compaction was added with the V-wheel roller. The soil surface was then leveled and then flat rolled.

For each of the first three experiments to assess tip design, a randomized complete block experimental design was used with four replications of four treatment depths. The treatment depths were 100, 175, 250, and 325 mm. These depths were selected so that the 175 and 325 mm depths would be 25 mm below the tillage-induced pans and would be located near where the maximum soil density was expected. The pan thickness was measured and was approximately 25 mm thick. These experiments were also used to determine the effect of tillage depth on the OSSS's ability to sense horizontal soil strength.

The fourth experiment was designed to assess the ability of the OSSS to measure horizontal soil strength as the unit moved vertically through the soil profile. A randomized complete block experimental design was also used for this experiment. This fourth experiment had four replications of two treatments. The treatments in this test were the direction of travel of the OSSS, i.e., either upward or downward through the soil profile.

A soil profile with one pan was created for the fourth experiment. This condition allowed comparison of how well the OSSS detected and vertically referenced soil strength as compared to a soil cone penetrometer. The pan was created at a depth of 200 mm by using a moldboard plow to laterally move the surface soil and then using a rigid wheel to pack the soil left exposed in the plow furrow. A small amount of soil was packed at a time, and the entire procedure repeated until the entire bin was been traversed. Shallow compaction was applied with the V-wheel roller. The soil surface was leveled and flat rolled.

Ten penetrometer measurements were randomly taken per plot with a hydraulically operated penetrometer on the soil bin penetrometer car. This penetrometer had a computer-based data acquisition system capable of measuring soil strength every 5 mm through the soil profile to a depth of 600 mm. A cone with a base area of 323 mm^2 was used on the penetrometer (*ASAE Standards*, 2004a, 2004b). The penetrometer measurements were averaged for an overall plot mean for comparison against impedance readings collected with the OSSS unit.

Bulk density was determined by taking undisturbed core samples (53 mm in diameter) from the top 300 mm of the soil with a sliding hammer undisturbed core sampler. Two replications of samples were taken from each plot on 50 mm intervals. The samples were weighed before drying so that gravimetric and volumetric soil moisture content could be determined from the samples. The samples were then dried in a forced-air convection oven for 72 h at 105°C (Blake and Hartge, 1986).

RESULTS AND DISCUSSION

EVALUATION OF TIP POSITION ON IMPEDANCE MEASUREMENTS

The first test of the OSSS was designed to determine if the position of the prismatic sensing wedge relative to the OSSS shank affected measurements with the OSSS. Two tips were used in this test: the flush-mounted 625 mm^2 tip (ST1), and the 625 mm^2 tip that extended 30 mm in front of the shank (ST2).

Testing of ST1 was suspended after three test runs because the force on the wedge at the shallow depth was below 10% of the full-scale capacity of the force transducer (table 1). This low force level was of concern because the inherent variation of force transducers may be near 5% of the full-scale measurement capacity. The force on the wedge increased at a deeper depth (325 mm) to near 20% full-scale transducer capacity but was still at unacceptable levels.

When ST1 was replaced with ST2, force values measured at all depths increased sufficiently to allow valid data to be obtained from the OSSS (table 1). Results from this experiment favored ST2 and indicated that the position of the sensing tip affected the horizontal soil strength measured with the OSSS. Based on these findings, ST2 was used in further tests.

TEST OF THE EXTENDED 625 MM^2 IMPEDANCE SENSING TIP (ST2) AT STATIC DEPTHS

The OSSS unit was operated at four static depths to determine if the ability of the unit to determine horizontal soil strength was affected by depth of operation. To accomplish this, the OSSS measurements were compared to cone penetrometer measurements at the depth of operation. The term "wedge index" was coined to describe soil strength as measured with a prismatic wedge. Wedge index is the force measured on the wedge divided by the base area of the wedge. This is similar to cone index as described in ASAE standard S313.2 (*ASAE Standards*, 2004b). The cone index values were averaged over the effective depth range of the OSSS tip, i.e., the tip was 25 mm wide, therefore the cone index used to compare to the wedge index was the average cone index across the depths measured by the OSSS tip.

The wedge index measurements exhibited a fair amount of variability in the data collected within each plot (fig. 5). The data indicate a cyclic pattern of force measurement, which is similar to other research findings of soil-tool draft data (Gill and Vanden Berg, 1968). The data became less variable toward the end of the test run; this was likely caused by soil accumulating between the impedance sensing tip and the OSSS shank. The soil that accumulated between the tip and the shank could prevent free travel of the sensing tips and

Table 1. Effects of tip position and depth on force measurements with the OSSS.

Tip Position	Depth (mm)	Force Measured (kN)	Transducer Loading (% full scale)
Flush (ST1)	175	0.34	7.6
	325	0.87	19.6
Extended 30 mm (ST2)	100	0.49	11.0
	175	0.64	14.4
	250	1.48	33.3
	325	1.42	32.0

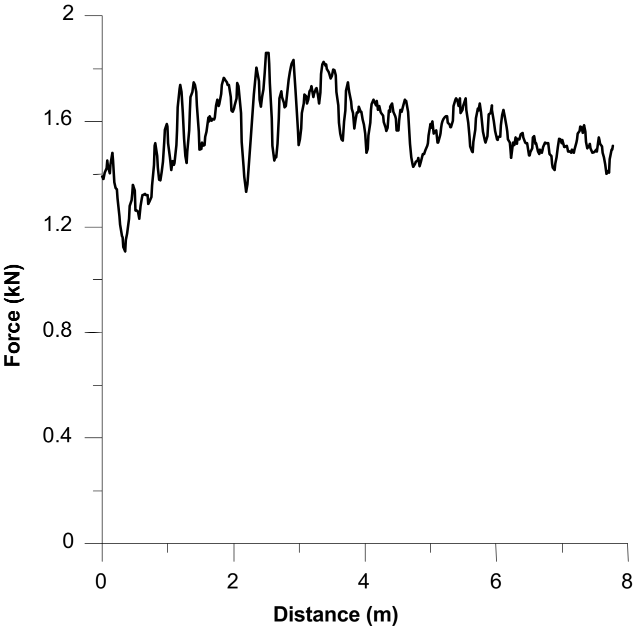

Figure 5. Force output from the OSSS with ST2 at 175 mm operating depth.

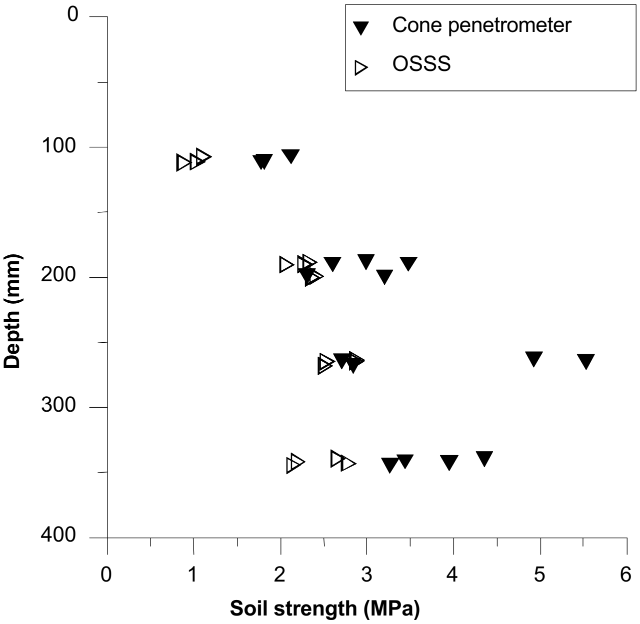

Figure 6. Soil strength profiles as estimated by the OSSS with ST2 and the cone penetrometer.

may justify further investigation into the use of ST3 to prevent this soil behavior.

The horizontal soil strengths measured with the OSSS were found to be less than the vertical soil strengths measured with the cone penetrometer, which agreed with findings of Alihamsyah et al. (1990) (fig. 6). Differences in soil shear patterns created by the design of the two tips could be the major reason for reduced impedance values as measured with the OSSS. The prismatic wedge design of the OSSS displaced soil laterally, so it was only loaded on the sides of the wedge. The cone displaced soil in all directions, and was therefore loaded from all directions. This additional loading could likely cause higher impedance to be encountered.

Soil moisture is an important factor that affects cone index measurements (Mulqueen et al., 1977). This is evident in the cone index data at the 265 mm operating depth (fig. 6), where the measurements varied by more than 2 MPa. However, the OSSS measurements did not have the same variation pattern. Upon inspection of the penetrometer data at this depth, the peak cone index values were found to have been measured in plots with lower moisture contents (data not reported). In addition, bulk density was found to be relatively constant at depths greater than 200 mm (table 2), similar to results obtained with the OSSS (fig. 6). Soil strength measured with the OSSS and ST2 did vary, but not to the same degree as soil strength measured with the soil cone penetrometer (fig. 6).

Depth affected the ability of the OSSS to detect soil strength; this was evident by examining the difference between the OSSS and cone penetrometer measurements at the different depths. Wedge index is approximately 50% less than cone index at the 100 mm depth. However, at the 175 mm depth, the two indexes approach unity. At operating depths deeper than 175 mm, the cone index again tends to be of greater magnitude than the wedge index. The indexes approaching unity at the 175 mm operating depth followed a trend observed in the previous test to determine the effect of tip position on impedance measurements (data not reported). One important point to consider about the indices coming to unity at the 175 mm depth is that this depth was below the surface compaction created by the V-wheel roller. The data from the penetrometer showed a low cone index in this region (fig. 7). The OSSS did not detect this reduction. At shallow operating depths, the soil flow across the wedge was not completely lateral. Some of the soil was lifted vertically, because there was not sufficient overburden to prevent upheaval. This could be a reason why the OSSS did not detect this relief. There may exist a shallow transition zone in which the OSSS is not capable of collecting valid soil strength data.

Regression analysis was used to relate the OSSS measurements to measurements made with the cone penetrometer. A linear equation was used to describe the relationship:

$$CI = 1.52 * WI \quad (1)$$

where CI is the cone index and WI is the wedge index. This model was significant ($P < 0.0001$), with an R^2 of 0.97 (fig. 8). All data fell within the 95th percentile confidence limits (fig. 8).

Force values on the force transducer were still reduced at the shallow depths (fig. 6). After evaluating the data from this test, the decision was made to increase the size of the impedance sensing tip. Increasing the size of the tip would also increase the force on the transducer. Increased transducer force could result in increased precision in measurements of soil strength near the soil surface as well as increased

Table 2. Bulk density and moisture content of OSSS with ST2 test.

Depth (mm)	Bulk Density ($g\ cm^{-3}$)	Gravimetric Moisture Content ($g\ g^{-1}$)
0-50	1.72	0.072
50-100	1.87	0.081
100-150	1.85	0.086
150-200	1.84	0.087
200-250	2.01	0.089
250-300	2.02	0.088
$LSD_{0.05}$	0.04	0.002
STD error	0.02	0.003

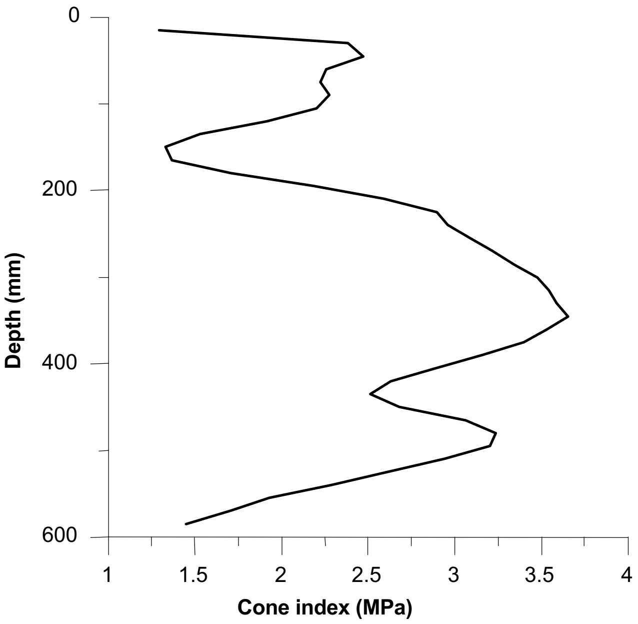

Figure 7. Cone index profile of the Norfolk sandy loam soil bin during the test of the OSSS with ST2.

confidence in the data. Soil could also be prevented from lodging behind the sensing tip as was hypothesized with ST2.

TEST OF THE 2500 MM^2 IMPEDANCE SENSING TIP (ST3) AT STATIC DEPTHS

The OSSS unit was again operated at four static depths of 100, 175, 250, and 325 mm. The force values recorded by the force transducer in this test (fig. 9) exhibited a more defined cyclic pattern than the force values in the previous test (fig. 5). The shape of ST3 tended to prevent soil from wedging between the tip and the OSSS shank, thus the reduction in measurement variation was not observed in this test, as it was in the previous test.

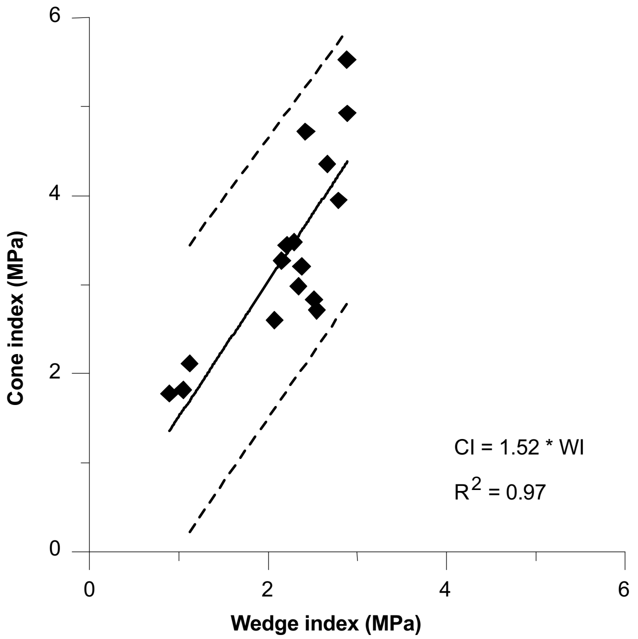

Figure 8. Regression output of the extended 625 mm^2 impedance tip test, wedge index compared to cone index.

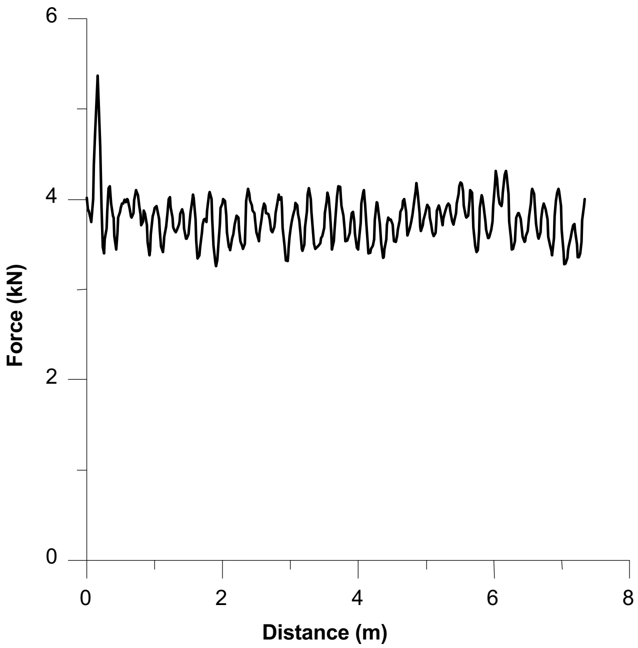

Figure 9. Force output from the OSSS with ST3 at 175 mm operating depth.

The data from the OSSS exhibited less variability than the cone penetrometer data (fig. 10). This observation was consistent with observations in the first two tests. Soil strength as measured with the cone penetrometer was greater in this test than in the second test (figs. 6 and 10). However, the wedge index measured in this test was lower than the wedge index measured in the second test.

The increase in cone index values was likely caused by reduced soil moisture content in this test as compared to the previous test with the ST2 (tables 2 and 3). These results agree with previous research, which determined that mois–

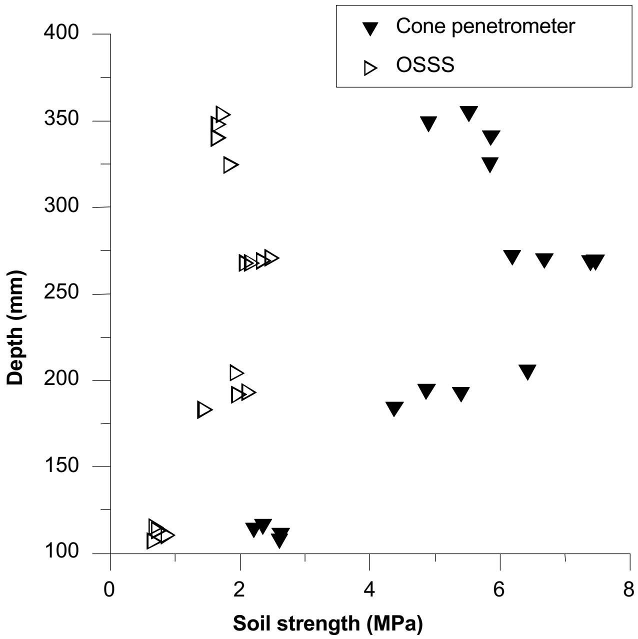

Figure 10. Soil strength profiles as estimated by the OSSS with ST3 and the cone penetrometer.

Table 3. Bulk density and moisture content of OSSS with ST3 test.

Depth (mm)	Bulk Density ($Mg\ m^{-3}$)	Gravimetric Moisture Content ($g\ g^{-1}$)
0-50	1.68	0.068
50-100	1.75	0.074
100-150	1.96	0.079
150-200	1.95	0.079
200-250	2.00	0.081
250-300	1.95	0.082
$LSD_{0.05}$	0.03	0.002
STD error	0.03	0.001

ture content inversely affected cone index readings (Blanchar et al., 1978; Cassel, 1983; Thangavadivelu et al., 1992).

The bulk density was also reduced in this experiment compared to the experiment with ST2 (tables 2 and 3). The decrease in bulk density is believed to be a plausible explanation for the decrease in wedge index between the ST3 and ST2 tests. The results of this test indicated that the OSSS may be more sensitive to bulk density changes and less sensitive to moisture changes. The cone penetrometer data indicated an opposite trend; soil moisture had a greater effect on cone index than bulk density. Conclusions from this test should be made cautiously, because the apparent cross-sectional area of the OSSS tip used in this test was quadruple the apparent cross-sectional area of the OSSS tip used in the previous test. The increased tip size could have contributed to reduced wedge index values. For example, if a layer of compacted soil is relatively thin in comparison with the size of the transducer, it would have a greater effect on ST2 than on ST3. The larger tip averages soil strength over a larger area, thus being less sensitive to discrete changes in soil compaction.

Regression analysis was performed on the two soil strength measurements to determine if a favorable relationship existed between the two methods. A linear relationship was found to exist between the wedge index and the cone index. The following equation describes the linear relationship (fig. 11):

$$CI = 2.99 * WI \qquad (2)$$

This relationship was found to be significant ($P > 0.0001$) with an R^2 of 0.98. The slope of the equation line is almost twice the slope of the ST2 regression equation. Since both measurement methods (CI and WI) are empirical and are affected differently by different factors, an absolute equation to relate the two measurements may not be possible. ST3 more closely correlated to cone penetrometer measurements than ST2 and was therefore selected as the best choice for dynamic horizontal and vertical soil strength testing.

Vertical and Horizontal Dynamic Testing of the OSSS with ST3

The OSSS was moved vertically through the soil profile at a rate of 0.1 $m\ m^{-1}$ of horizontal travel in this test to determine if the unit was capable of dynamic measurement of soil strength profiles. The OSSS was operated both upward and downward as it was moved forward at 0.45 $m\ s^{-1}$. The wedge index data obtained from the OSSS unit was compared to cone index data collected with the cone penetrometer to determine if direction of travel affected wedge index data. The results of the regression analysis did not indicate that the direction of travel affected wedge index readings (fig. 12).

The trend in previous tests of a depth effect on the OSSS measurements was again observed in this test. The OSSS was found to be ineffective in acquiring accurate soil strength data at depths less than 150 mm. This minimum depth of operation was determined by plotting the wedge index, cone index, and a percentage difference against depth (fig. 13). The OSSS was found to predict similar trends in soil strength data to those predicted by the cone penetrometer at depths greater than 150 mm (fig. 13). At depths greater than 150 mm, both measurement methods predicted the maximum soil strength within 5 mm of each other; the OSSS predicted the depth of maximum soil strength to be at 265 mm, and the cone penetrometer predicted the depth of maximum soil strength to be at 270 mm.

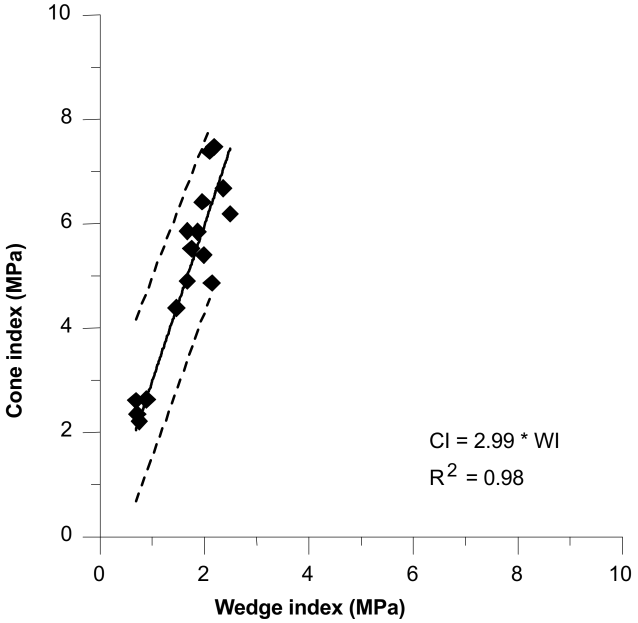

Figure 11. Regression output of 2500 mm² static depth test, wedge index compared to cone index.

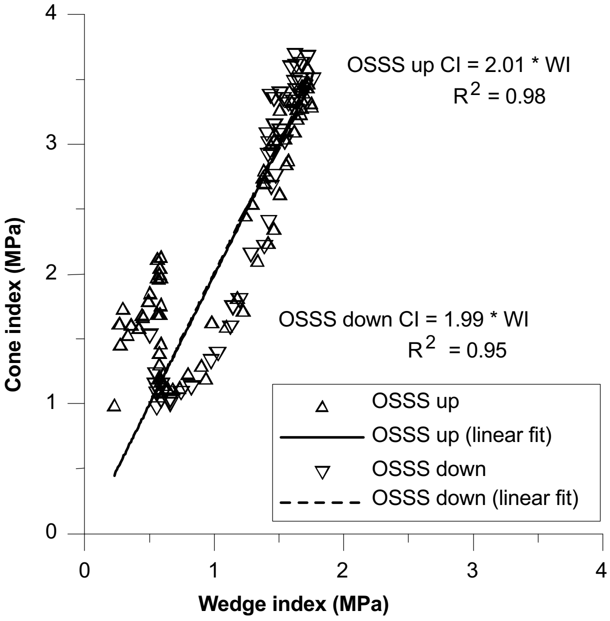

Figure 12. Comparison of the effect of the direction of vertical travel on wedge index readings.

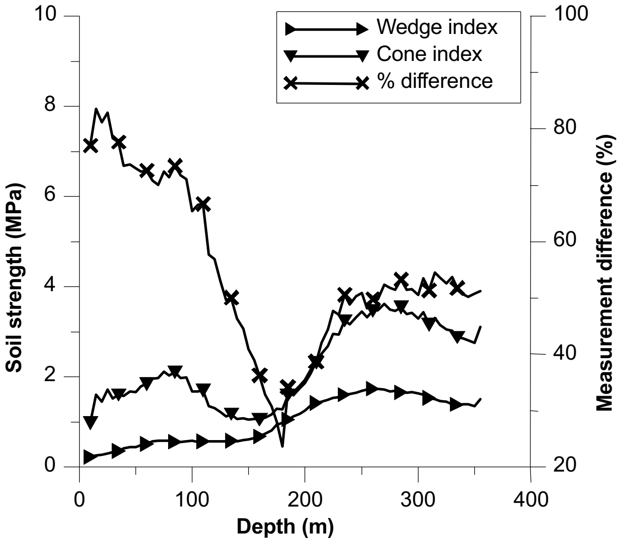

Figure 13. Wedge index, cone index, and index differences by depth.

The wedge index did not have a strong correlation to cone index when the depth of operation was less than 150 mm (fig. 14). However, the wedge index was found to favorably agree with the cone index in this experiment at depths greater than 150 mm (fig. 14). This observation is consistent with observations in previous tests, and points to a critical operation depth that is necessary for accurate data acquisition.

Wedge index was found to be more closely related ($P > 0.0001$, $R^2 = 0.74$) than the cone index to bulk density averaged over 50 mm depth increments (fig. 15). The cone penetrometer measurements were found to be related to bulk density averaged over 50 mm depth increments; however, the relationship was not as strong ($P > 0.0001$, $R^2 = 0.55$) (fig. 15). The linear relationship between bulk density and wedge index was strengthened when the depth effect was taken into account (fig. 16). The relationship between bulk density and cone index was adversely affected when the depth effect on wedge index was taken into consideration (fig. 16). This relationship of wedge index to bulk density must be considered carefully, because bulk density was determined on 50 m depth increments, and specific bulk density at distinct depths within the 50 mm average could vary substantially. The OSSS does, however, follow the average well, and could be useful in quick determination of bulk density profiles of the soil.

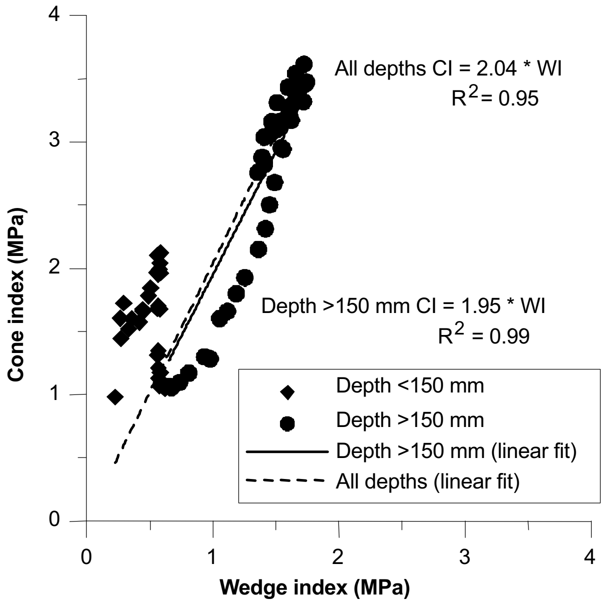

Figure 14. Dynamic depth test results, plotting wedge index against cone index.

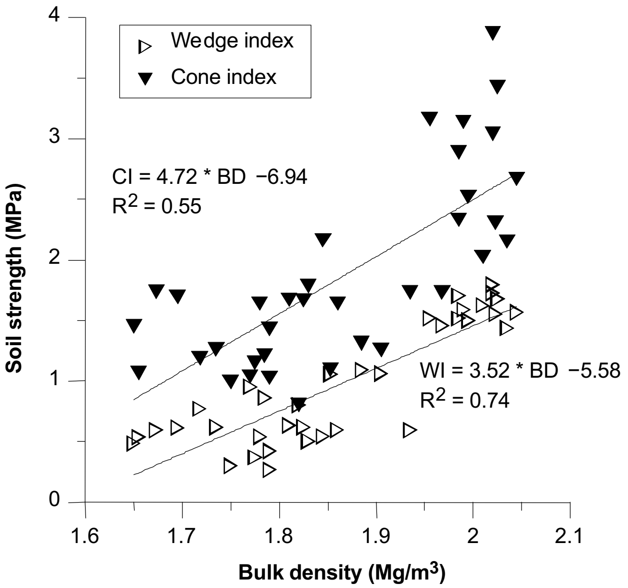

Figure 15. Dynamic depth test results, plotting wedge index and cone index against bulk density (all depths of operation).

CONCLUSIONS

Soil compaction is a major soil physical problem that limits root growth and yield in crops. A scientific approach to adjusting this soil physical property has been hindered by

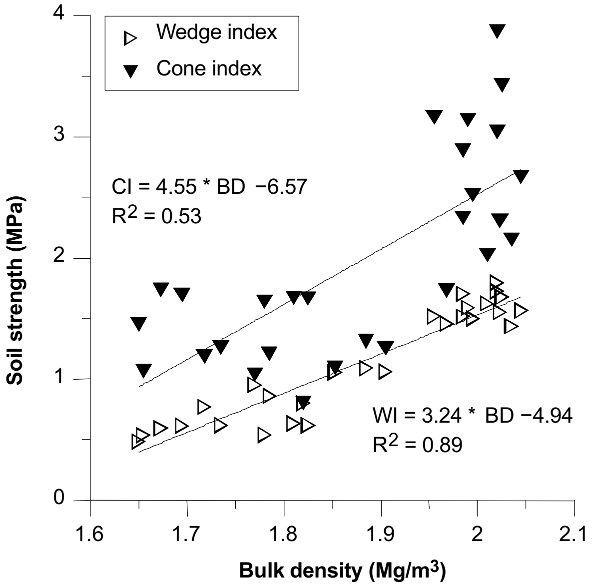

Figure 16. Dynamic depth test results, plotting wedge index and cone index against bulk density (depth >150 mm).

the inability of rapid measurement. The OSSS was designed to provide a method of rapid determination of soil physical properties contributing to soil compaction.

The OSSS is a tool that empirically measures soil physical properties to determine soil compaction levels. The OSSS, like the cone penetrometer, is affected by soil properties as well as physical properties of the tool. The position of the impedance sensing tip, in reference to the front of the shank, was found to affect the ability of the OSSS to accurately measure soil strength. The size of the tip was also found to affect soil strength measurements. A single equation to relate wedge index to cone index does not appear possible due to variation in sensitivity of the two measurement methods to soil conditions, i.e., moisture content.

The OSSS was able to predict the bulk density profile in the soil, which is the physical soil property modified to reduce soil compaction. The OSSS measurements also agreed favorably with cone penetrometer measurements of the soil profile at depths greater than 150 mm. The OSSS was determined to be less influenced by moisture content of the soil. Therefore, it was more closely correlated to bulk density than the cone penetrometer. Therefore, this tool may be more suited for soil compaction measurements than a cone penetrometer, because of the insensitivity to moisture content.

Preliminary evaluation of the OSSS, in a coastal plains soil, indicates that this tool has the potential of measuring soil strength below 150 mm. The OSSS needs to be evaluated over a wider range of soil conditions and soil types to completely assess the ability of this tool as a general soil strength measuring device.

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