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Characterization of Cone Index and Tillage Draft Data to Define Design Parameters for an On-the-go Soil Strength Profile Sensor

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Abstract: Precision agriculture aims to minimize costs and environmental damage caused by agriculture and to maximize crop yield and profitability, based on information collected at within-field locations. In this process, quantification of soil physical properties, including soil strength, would be useful. To quantify and manage variability in soil strength, there is need for a strength sensor that can take measurements continuously while traveling across the field. In this paper, preliminary analyses were conducted using two datasets available with current technology, (1) cone penetrometer readings collected at different compaction levels and for different soil textures and (2) tillage draft (TD) collected from an entire field. The objective was to provide information useful for design of an on-the-go soil strength profile sensor and for interpretation of sensor test results. Analysis of cone index (CI) profiles led to the selection of a 0.5-m design sensing depth, 10-MPa maximum expected soil strength, and 0.1-MPa sensing resolution. Compaction level, depth, texture, and water content of the soil all affected CI. The effects of these interacting factors on data obtained with the soil strength sensor should be investigated through experiments. Spatial analyses of CI and TD indicated that the on-the-go soil strength sensor should acquire high spatial-resolution, high-frequency ($\geq$ 4 Hz) measurements to capture within-field spatial variability.

Keywords: Soil Compaction, Soil Strength, Sensor, Cone Index, Tillage Draft

Introduction

Precision agriculture, also called site-specific crop management (SSCM), is the quantification and management of variability induced by natural phenomena and human activities in agricultural fields. Soil properties are some of the most important factors to consider when implementing SSCM. Soil physical and chemical properties govern the transport of nutrients and water through the soil and the amount of plant available nutrients and water (Barber, 1984).

Soil compaction, the action of soil becoming more compact, is a concern in crop production. Soil compaction often restricts root development and growth (Lipiec and Stepniewski, 1995) through increased bulk density and/or soil strength (Guerif, 1994), and reduces the biological activity of plant roots and organisms in the soil because of reduced aeration of the soil (Voorhees et al., 1975). Compaction also increases environmental risks such as soil erosion and global atmospheric warming due to increased emission of CO_2, CH_4, and N_2O (Horn et al., 1995), and reduces quality of surface waters and ground waters (Soane and Van Ouwerkerk, 1995). The causes of soil compaction and the resulting soil deformations may be different in the various soil layers (i.e., top layer, arable layer, and subsoil) (Koolen and Kuipers, 1983).

The degree of soil compaction, called compactness, traditionally has been determined through laboratory tests with soil samples and expressed as pore space, void ratio, or dry volume weight (Koolen and Kuipers, 1983). Another approach to estimate the state of soil compaction is to measure soil strength (Canarache, 1991). Laboratory determination of either soil compactness or soil strength at the spatial resolution needed in SSCM is time-consuming, laborious, and expensive even if the required, spatially dense sampling is possible.

To overcome the limitations of laboratory tests, field sensors have been developed to quantify soil properties related to soil compaction or soil strength. The cone penetrometer is perhaps the most widely used tool for quantifying soil strength. The index of soil strength measured by a cone penetrometer, cone index (CI), is defined as the force per

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unit base area required to push the penetrometer through a specified small increment of depth. The shapes and operating conditions of standard cone penetrometers are documented in ASAE Standard S313.3 (ASAE, 2003a) and ASAE Engineering Practice EP 542 (ASAE, 2003b). Many engineers have adapted the standard penetrometer design to improve the speed and/or accuracy of data collection. For example, Raper et al. (1999) developed a multi-probe cone penetrometer that could be tractor-mounted and used to obtain multiple CI profiles at a location more quickly and easily. Cone penetrometer readings, however, are discrete point measurements and it is difficult to collect CI data at enough points to provide an accurate picture of spatial variations in soil strength. Even in nonspatial analyses, researchers have often collected hundreds of penetrometer readings to investigate treatment differences (e.g., Busscher et al., 1986).

Another way to estimate the state of soil strength is to use tillage implement draft. McLaughlin and Burtt (2000) investigated the suitability of spatial measurements of implement draft, tractor fuel consumption, engine speed, and ground speed for mapping tillage energy. Maps for primary tillage showed lines of higher implement draft when traversing subsurface drain tiles, and higher draft in some of the depressions in the field. Van Bergeijk et al. (2001) measured plow draft to locate different topsoil types in a field. Draft maps corresponded well with clay content as shown by the soil survey, while providing a higher spatial resolution. Even though tillage draft can estimate soil strength, the measurement is not very specific, since it is integrated over the operating depth and width of the tillage tool, rather than measuring conditions at a single depth.

A soil strength sensor that can take measurements at multiple depths continuously while traveling across the field would have potential for both research and production use. With proper resolution in the horizontal and vertical directions, the soil strength sensor would find several applications in SSCM, such as assessment of variability in soil conditions, delineation of compacted areas and detection of locations of restrictive layers (e.g., claypans). A number of researchers have attempted continuous measurement of soil strength at multiple depths (Glancey et al., 1989; Chukwu and Bowers, 1997; Adamchuk et al., 2001; Andrade et al., 2001).

This paper reports on preliminary data analysis conducted as a part of the research to design and evaluate a prototype on-the-go soil strength profile sensor. The purpose of the on-the-go soil strength profile sensor is to obtain "CI-like" soil resistance measurements with a soil-penetrating tip more rapidly and with a higher spatial resolution than is feasible with a cone penetrometer, and to detect spatial and vertical variability of soil strength under field conditions. The design concept of the sensor (fig. 1) was based on the following requirements: (1) capable of obtaining measurements accurate enough in resolution and sufficient in number to quantify spatial variability in soil strength; (2) a dynamic sensing range greater than the expected range of soil strength, coupled with a sensing resolution and frequency high enough to detect meaningful differences in soil strength; and (3) for sensing at multiple depths, the location and

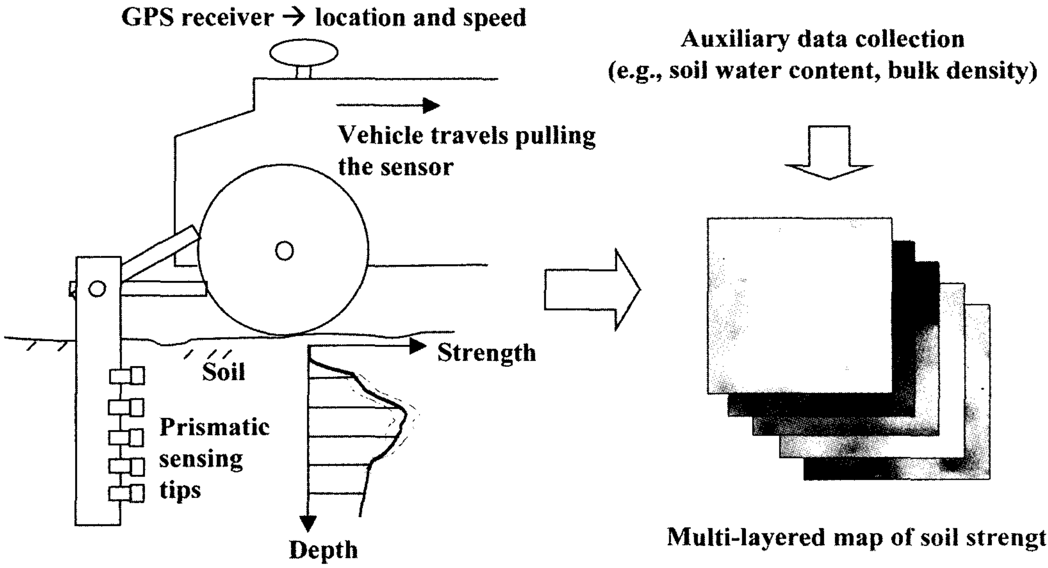

Fig. 1 Operational concept of the on-the-go soil strength profile sensor: field data collection using the sensor, auxiliary data collection, and a resultant multi-layered soil strength map.

spacing of sensing elements should be minimize interference between adjacent elements. Interpretation and application of data collected by the soil strength sensor also requires a good understanding of local variability in those soil conditions affecting soil strength. Literature review shows that bulk density, texture, water content, and soil depth are generally the most significant factors affecting not only soil strength, but also root development and crop growth (Perumpral, 1987; Ohu et al., 1988; Guerif, 1994).

The overall objective of this research was to analyze available soil strength datasets to obtain information useful for sensor design and for development of field test and data analysis procedures. Two specific objectives were (1) to characterize cone index and tillage draft using visual inspection, statistical methods, and variogram analysis, and (2) to obtain general guidelines for design of the on-the-go soil strength profile sensor and information useful for interpretation of sensor test results.

Materials and Methods

1. Data Collection

Cone penetrometer readings (CI, MPa) and tillage draft force (TD, kN) were collected on a field (35 ha, 790 m x 455 m) located near Centralia, in central Missouri (39.230 N, 92.117 W). The soils found at the site were of the Mexico series (fine, smectitic, mesic aeric Vertic Epiaqualfs) and the Adco series (fine, smectitic, mesic aeric Vertic Albaqualfs). These soils were formed in moderately fine-textured loess over a fine-textured pedisediment and were classified as somewhat poorly drained. Surface textural classes ranged from silt loam to silty clay loam. The subsoil claypan horizon(s) were silty clay loam, silty clay, or clay, and commonly contained as much as 50 to 60% smectitic clay. Topsoil depth above the claypan (depth to the first Bt horizon) ranged from less than 10 cm to greater than 100 cm. The field had been managed in a corn-soybean rotation since 1990 (Sudduth et al., 2003).

The cone penetrometer (fig. 2, left) used in data collection was developed by USDA-ARS at Columbia, Missouri. It was a self-contained, tractor-mounted, hydraulically-powered device that could insert five cone penetrometers, spaced 0.19 m apart, into the soil simultaneously, similar to the system developed by Raper et al. (1999). CI values up to a 1-m depth were recorded with a 0.5-cm increment in corn stubble prior to tillage (March 25, 2002), and CI profiles were developed. Data were obtained following the scheme in fig. 3, to investigate the patterns of CI for different compaction levels and soil textures. Areas were selected based on knowledge of the field obtained from previous research (Sudduth et al., 2000; Sudduth et al., 2003). For different compaction levels, five-probe readings were taken at 10 locations starting at the field edge with a 1.84-m nominal spacing (area A, fig. 3). Higher CI values were expected in the end rows and lower CI values in the remainder of the field. To investigate the effects of soil texture on CI, two areas about 12 m by 12 m were selected. Averaged over a 0- to 90-cm depth, area B (fig. 3) had a higher clay content (39%) and a lower silt content (57%), while area C had a lower clay content (22%) and a higher silt content (75%). Five-probe penetrometer readings were taken at 30 locations within each area. Two soil samples were also taken to a depth of 90 cm in each of the two areas at the time of penetrometer data collection, and gravimetric soil water content (%, dry basis) was obtained with a 15-cm depth increment.

Chisel plow tillage draft was collected with a 0.2-m nominal operating depth, a 7-m nominal operating width, a 2-m s^{-1} nominal travel speed, and a 1-Hz sampling frequency (fig. 2, right). Tillage draft was measured using the standard 3-point hitch electronic draft sensing system on an AGCO[1] (AGCO Corp, Duluth, Ga.) row crop tractor. A drawbar was fabricated to span between the hitch draft links

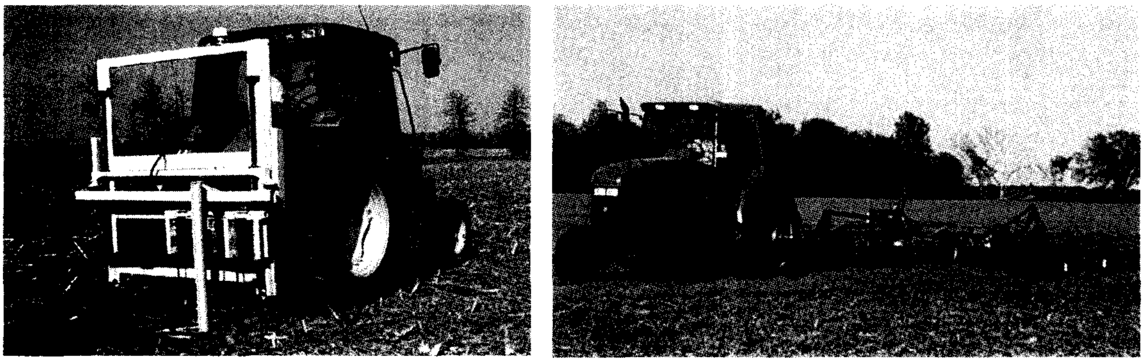

Fig. 2 Data collection for cone index (CI, left) and tillage draft (TD, right).

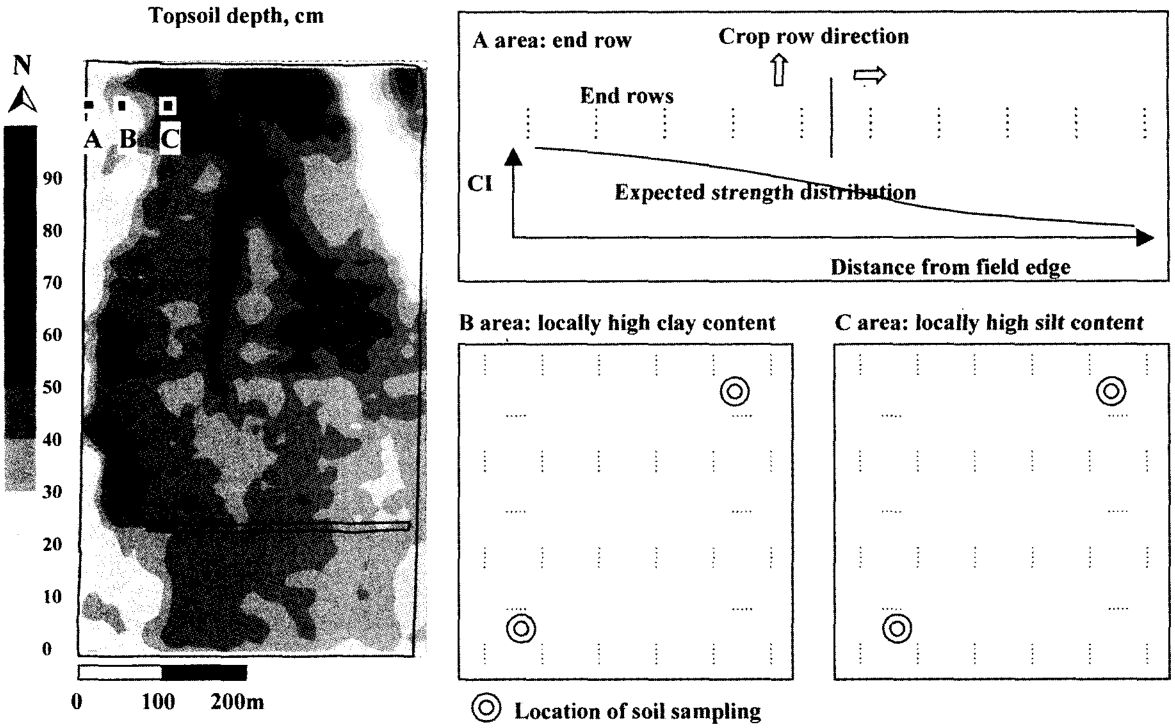

Fig. 3 CI data collection scheme: selected areas overlaid on a map of topsoil depth (left), 10 locations to investigate difference in compaction level between end rows and remainder of field (right, top), and 30 locations each for area B and area C (right, bottom).

for chisel plow attachment. A draft-sensing pin located at the attachment of each draft link to the tractor frame provided an analog voltage proportional to draft. These signals were recorded with 12-bit resolution using a DaqBook/100 data acquisition system (Iotech Inc., Cleveland, Ohio) and a laptop computer located in the tractor cab. The rated load of each sensing pin was ± 60 kN, and the manufacturer's stated accuracy was ± 4% of the sensing range (5 kN) or better. Position information was obtained using an RTK-DGPS (real time kinematic differential global positioning system) with an accuracy of approximately 5 cm. More than 23,000 draft values were collected over the entire field.

2. Analytical Procedures

The five CI profiles obtained for each sampling location were averaged to create a single profile. Mean CI values were calculated from each profile over 20-cm depth intervals (i.e., 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm) and used for statistical analysis. Analysis of variance and Duncan's multiple range test were applied using SAS version 8.01 (SAS Institute Inc., Cary, N.C.) to investigate statistical significance of the effects of soil texture and depth.

Variogram analysis, or geostatistics, was applied to the depth-averaged CI values for the two soil texture areas, and to the TD data for the entire field. Variogram analysis is the primary tool of spatial variability analysis and has been used extensively to analyze precision farming data (e.g., Chung et al., 2000). Unlike conventional non-spatial statistics, geostatistics can be used to analyze spatially dependent data, and provide information on the ranges over which variables are spatially dependent. The variogram characterizes the spatial variability structure of measurements with parameters such as nugget variance (semivariance, γ, at zero lag distance due to small scale or measurement errors), sill variance (maximum semivariance), and range (lag distance at which semivariance reaches its sill). Range indicates the limit of spatial dependency. The most common geostatistical model, the single variogram, may not adequately fit field data in those cases where multiple spatial structures are present due to interactions of variables and processes. In such cases, a nested variogram, which is the linear combination of single variograms, may capture the more complex patterns of variability (McBratney and Webster, 1986).

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1) Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by NIAE, Korea or USDA-ARS, USA.

For depth-averaged CI data, the active lag and lag interval used in the geostatistical analysis were 6 m and 0.5 m. These values were chosen considering the size of the areas and number of pairs within each lag interval, respectively. For TD, single and nested models were fit to the TD variogram. TD values were expressed in percentage of the maximum value (i.e., 100% = 37.7 kN) for the analysis. Active lag distance was varied from 1 m to 20 m on a 0.2-m increment, and from 20 m to 200 m on a 2-m increment. Based on past experience (Chung et al., 2001), several nested models were evaluated: Gaussian-spherical, Gaussian-exponential, double spherical, triple spherical, and Gaussian-spherical-exponential. S+SpatialStats version 1.5 (MathSoft, Inc., Seattle, Wash.) was used for the variogram analysis.

Results and Discussion

1. CI Pattern and Effect of Compaction Level

CI profiles were investigated visually to observe spatial variability in soil strength over the selected areas as well as soil strength variability as a function of depth. To remove any micro-scale variability and focus on the effect of end row compaction, CI values from the five probes spanning 0.76 m were averaged. As shown in fig. 4, averaged CI profiles from different compaction levels did not differ greatly in overall shape. Near the soil surface, CI increased as depth increased with the first (i.e., nearest the soil surface) local maximum CI (about 2 MPa) around a 20-cm depth. CI then decreased with depth to about a 50-cm depth and increased monotonically after that.

Vertical variation of CI was more dynamic than spatial variation and a large portion of the variation occurred at depths less than about 50 cm. Local extrema of the CI profile, at approximately 20-cm and 50-cm depths in this case, indicated that there might be changes in soil physical properties (e.g., bulk density, clay content) between these points. In an agronomic sense, the first maximum CI and depth to the maximum CI are important since nutrient uptake by the plant in the early stages of crop growth takes place near the soil surface and a high CI in this area could limit root growth and penetration. Also, soils with high CI values near the surface would reduce water infiltration into the root zone. Therefore, soil strength sensing at multiple depths, especially depths shallower than 50 cm, would be useful for understanding soil conditions and could be used to provide information that might guide field operations to provide a better environment for crop growth.

Fig. 5 shows the changes in maximum CI and depth to the maximum CI near the field edge. Maximum CI was higher (around 2.5 MPa) in the end rows and decreased to around 2 MPa as the sampling position moved to within-field. This pattern was expected, since end rows experience more wheel traffic than does the remainder of the field. Depth to the maximum CI did not show a clear pattern, but was slightly shallower (17 cm) in the end rows and deeper (20 cm) at within-field locations. It should be noted that determination of maximum CI and depth to the maximum CI was somewhat subjective because CI values did not always show a clear single peak. In design of a soil strength sensor with multiple tips, the resolution of force sensing should be selected considering the expected variation in CI and the spacing between tips should be determined con-

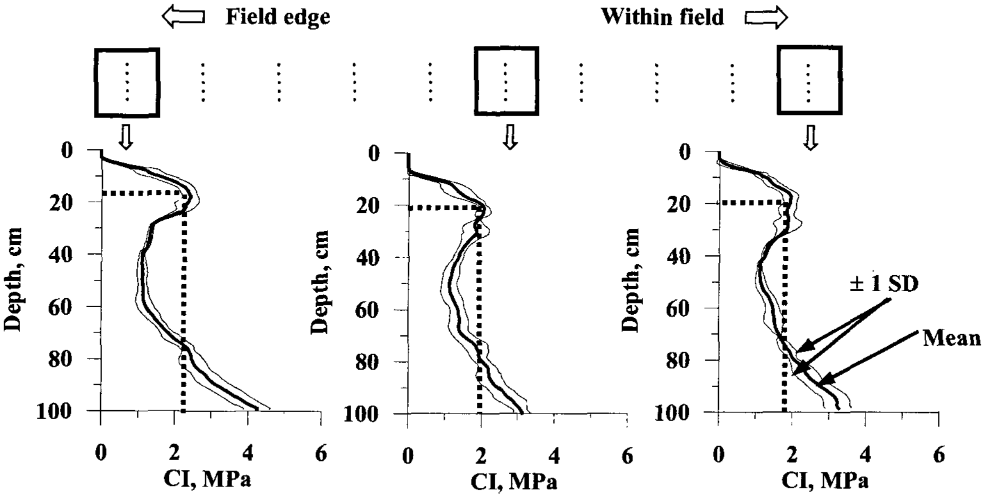


Fig. 4 Mean ± 1 standard deviation of CI values from five-probe penetrations at different locations from end row (left) to within-field (right).

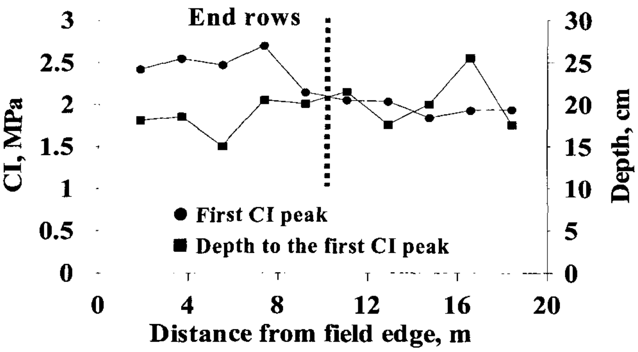


Fig. 5 Value of the first maximum CI and the corresponding depth as a function of distance from field edge, showing higher compaction in end-row area.

sidering the vertical variation in soil strength.

2. Effect of Texture, Depth, and Water Content

Fig. 6 shows representative CI profiles and duplicate water content profiles for areas B and C. Patterns of CI profiles were quite different between the two areas while they were similar in shape within each area. CI variations among the five probes and complexity of the profiles were greater in area C, while CI difference with depth was greater in area B. CI values in the two areas were similar at depths shallower than about 60 cm, but at greater depths CI increased more quickly in area B.

It is generally accepted that soil strength is higher with lower water content, higher bulk density, and greater depth (e.g., Ayers and Perumpral, 1982; Elbanna and Witney, 1987). As expected, area B (higher clay content, lower density, and higher cohesion) exhibited a higher CI, especially at greater depths and lower water contents. Effects of depth and water content were clearly explained in CI patterns of area B, where CI increased with depth and decreased at higher water contents. Effects of depth and water content were not as clear in area C, but the smaller increase in CI values below 60 cm, relative to that seen for area B, might possibly be attributed to the increasing water contents. Based on the results, it was concluded that good interpretation of CI profiles would require information on soil strength factors such as water content, bulk density, and texture.

CI values were analyzed statistically using analysis of variance (ANOVA) to investigate the effect of soil texture and sensing depth. CIs were averaged over 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths. There were a total of 1,500 averaged CI values (30 locations, 5 probes, 2 textures, 5 depths). Mean, minimum, and maximum CI were 1.78, 0.17, and 7.33 MPa, respectively. The maximum CI, 7.33 MPa, occurred at the 80-100 cm depth in area B. Analysis of variance showed that 20-cm-depth-averaged CIs were significantly different ($P<0.01$) for different soil textures and sensing depths. The results of Duncan's multiple range test for different depths are sum-

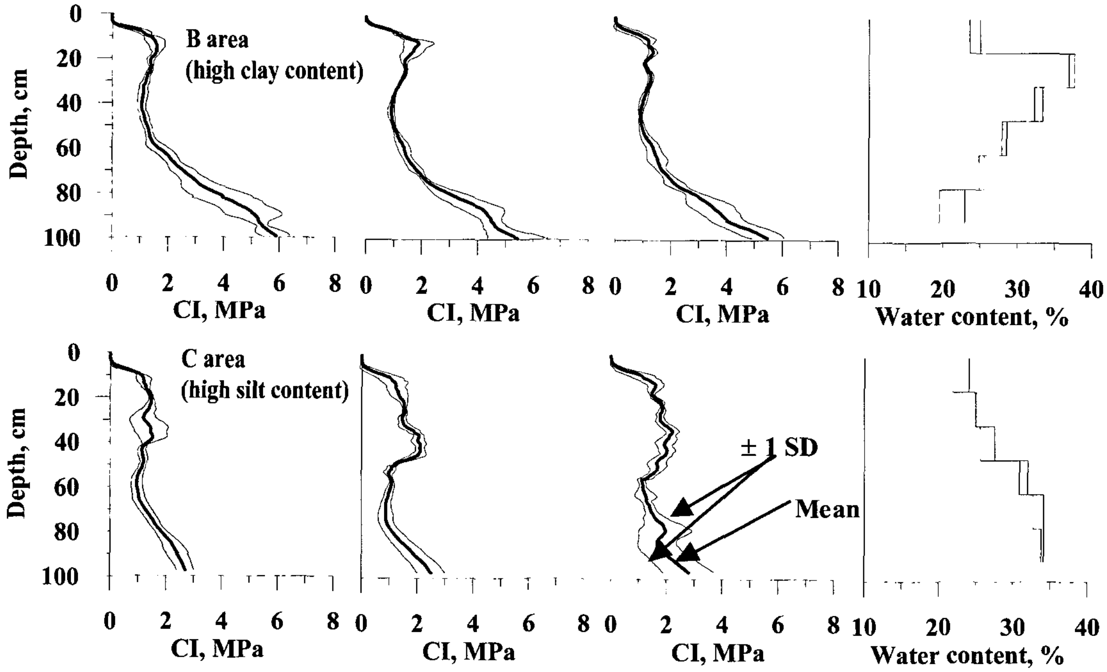


Fig. 6 Selected CI profiles and duplicate water content profiles from areas B (top) and C (bottom).

marized in table 1. Overall, CI was higher in area B (2.09 MPa) than in area C (1.47 MPa), and increased as sensing depth increased. CIs at 20-40 cm and 40-60 cm were not significantly different, but CIs at 20-40 cm were slightly greater. This suggested that the first CI peak generally occurred in the 20-40 cm depth range, within the 50-cm desired sensing depth. The maximum soil strength observed in this dataset was 7.33 MPa. Therefore, a design maximum expected soil strength of 10 MPa seemed appropriate, considering the effects of dynamic operation of an on-the-go sensor and the need for a safety factor. The required resolution for the sensor was based on the variations in soil strength shown in table 1. Critical values for mean separation in these data were 0.14 MPa and 0.09 MPa for depth and texture, respectively. Therefore, a sensing resolution of 0.1 MPa (1% of the maximum expected soil strength) was chosen as appropriate to detect significant differences in soil strength.

In design of a soil strength sensor, it is necessary to obtain a sufficient number of measurements to describe the variability in, and patterns of, soil strength. For a sensor moving horizontally and measuring soil strengths at multiple depths, the amount of data required depends on the number of sensing elements on the sensor body and the frequency of data acquisition. Within the upper 50 cm, the general shape of the CI profiles could be represented by a smooth curve with two to four local extrema. A fifth order polynomial from five samples and a boundary condition at the soil surface would give a good approximation of the CI profiles, especially if the measurements were taken near the extrema. Since there could be sensing errors and micro-scale soil strength variability in actual data collection, the number of measurements should be several times greater than the number of local extrema to accurately represent the curve. This issue could be resolved either by increasing the number of the sensing elements or by combining several consecutive CI profiles collected by a small number of sensing elements. However, the first approach is impractical because the number of sensing elements is limited due to issues in construction and cost as well as possible reductions in accuracy due to interactions between elements. Rationales supporting the combination of CI profiles are: (1) CI profiles were not significantly different within small distances (e.g., within relatively homogeneous soil texture areas), and (2) soil strength factors such as soil texture and water content would not vary much within short distances (e.g., a few meters).

Table 1 Variations in mean CI as a function of depth (left) and soil texture (right)

Depth, cm	Mean CI, MPa	Grouping
0-20	0.80	a[a]
20-40	1.56	b
40-60	1.44	b
60-80	1.86	c
80-100	3.24	d

Soil texture	Mean CI, MPa	Grouping
High silt content	1.47	a
High clay content	2.09	b

[a] Means with the same letter are not significantly different based on Duncan's multiple range test (α=0.05). Critical values for means separation between two categories were 0.14 MPa for depth and 0.09 MPa for soil texture.

3. Spatial Variability in CI and TD

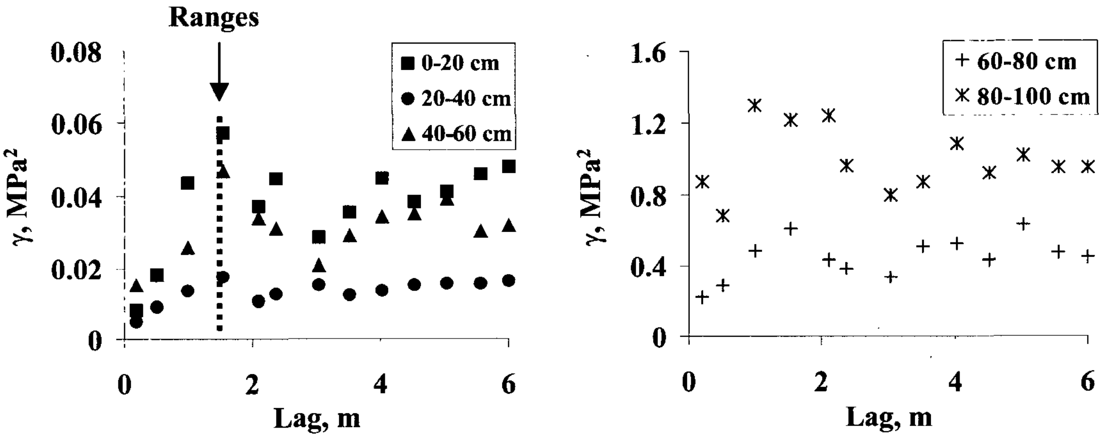
Variogram analysis was used to investigate the spatial dependency of CI for different soil textures and sensing depths. A variogram was obtained at each depth level for area B (fig. 7a) and area C (fig. 7b). From visual examination, none of these data exhibited nested structures in the variability, and therefore all could be represented by single variograms. Semivariances for area C were higher at shallower depths and lower at greater depths than those for area B. For area B, semivariances were lower (<0.06 MPa^2) at shallower depths (<60 cm) and increased up to 1.3 MPa^2 at greater depths. Semivariances did not increase much as depth increased in area C. Sill variances were higher as soil depth increased, indicating a higher level of CI heterogeneity, with the exception of a higher sill at the 0-20 cm depth of area B. The variograms at depths shallower than 60 cm showed ranges between 1 and 2 m, while nugget variances or noise effects dominated at depths greater than 60 cm. The repeating pattern of CI at 1- to 2-m ranges was attributed to the long-term effects of field machinery traffic and tillage.

From the variogram analysis, we concluded that (1) CI variability was dependent on soil texture and sensing depth, (2) soil compaction due to long-term effects of field machinery was apparent at depths shallower than 60 cm, and (3) the pattern of the compaction depended on soil texture and depth. Data sampling theory dictates that, to detect patterns of soil strength with 1- to 2-m ranges, at least two samples are required within 1 m. The required sampling frequency would also depend on travel speed of the soil strength profile sensor. If the sensor is designed to operate at a normal tillage speed of 2-m s^{-1}, the data acquisition frequency should be greater than 4 Hz to detect the 1- to 2-m repeating pattern in soil strength.

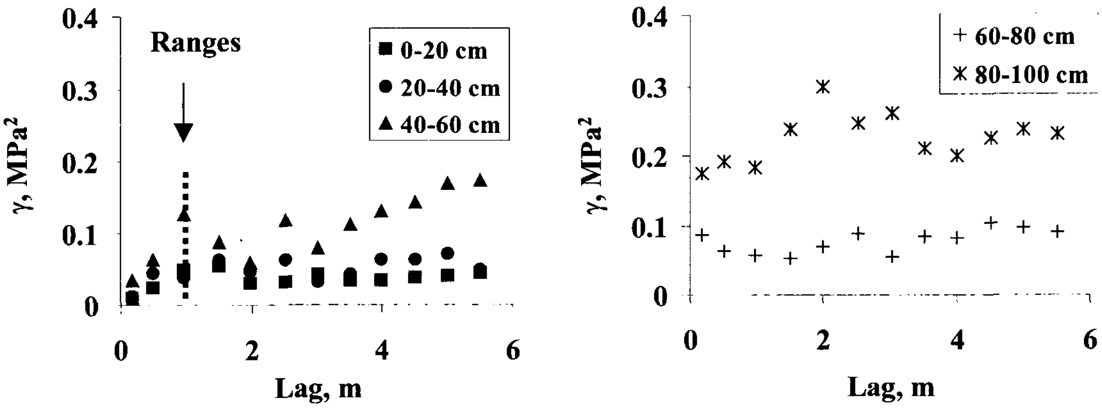
To visualize the soil strength distribution, CIs were kriged with a 0.12-m grid spacing for each depth level using Surfer version 7.0 (Golden Software Inc., Golden, Colo.). The resulting soil strength maps for areas B and C in fig. 8 show not only the spatial pattern of CI at a single depth but also quite different CI distributions at the different textures and depths. Therefore, on-the-go sensing of soil strength at multiple depths would provide useful information on soil conditions and a high vertical sampling frequency would be preferable to provide more accurate soil strength maps.

The TD map of the field was visually investigated to examine the overall spatial pattern, and variogram analysis was applied to quantify the structure. The TD map (fig. 9, left) showed three possible spatial structures: (1) a long range structure, with greater TD at the north of the field and lower TD in the south of the field, (2) a short range structure, comprised of small areas of different TD levels, overlaid on the long range structure, and (3) a noise component, consisting of abrupt changes in TD.

Variograms of TD with active lags of 20 m and 200 m are shown in fig. 9, right. In the variogram with a 20-m active lag, semivariances were scattered at lag distances smaller than about 7 m, and then showed a repeating pattern at lag distances greater than 7 m. The scattered semivariances were attributed to the nugget effect within the 7-m tillage transect width. The period of the repeating pattern was also about 7 m, similar to the distance between the tillage transects. Variograms fit to the data also confirmed that there were spatial structures with ranges of about 2 m and 10 m (results of the model fit not presented here). The variogram with a 200-m active lag also showed scattered semivariances at lag distances smaller than about 100 m. The first range was seen at a lag distance of about 10 m. The slope of the variogram graph flattened and reached the sill variance at a lag distance of about 130 m. Models fit

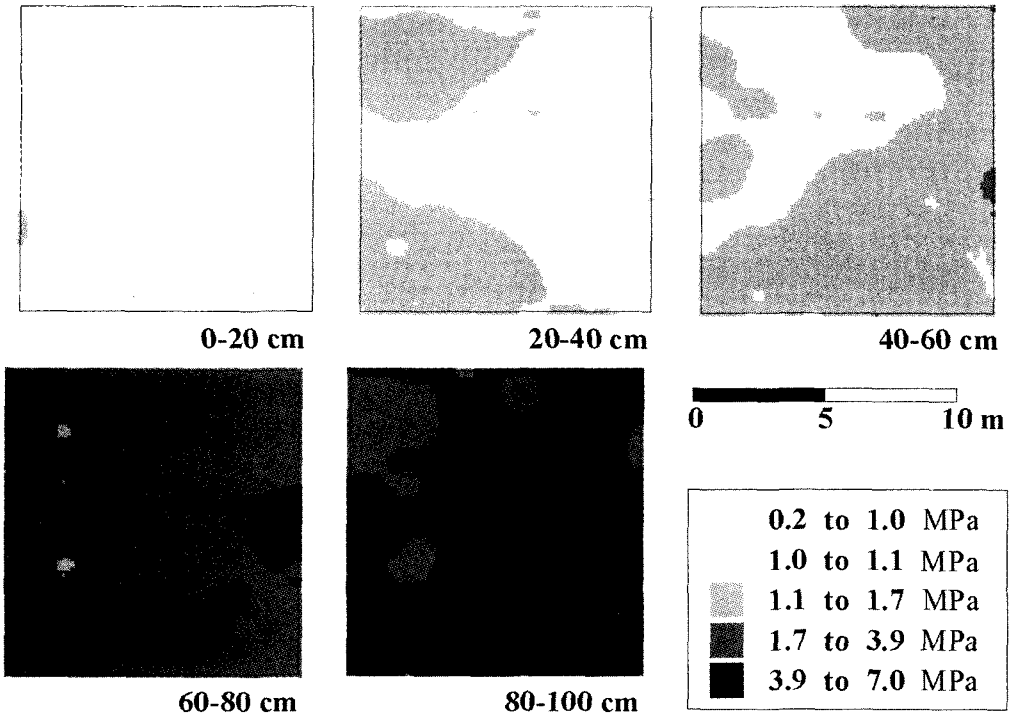


(a) Area B: high clay content

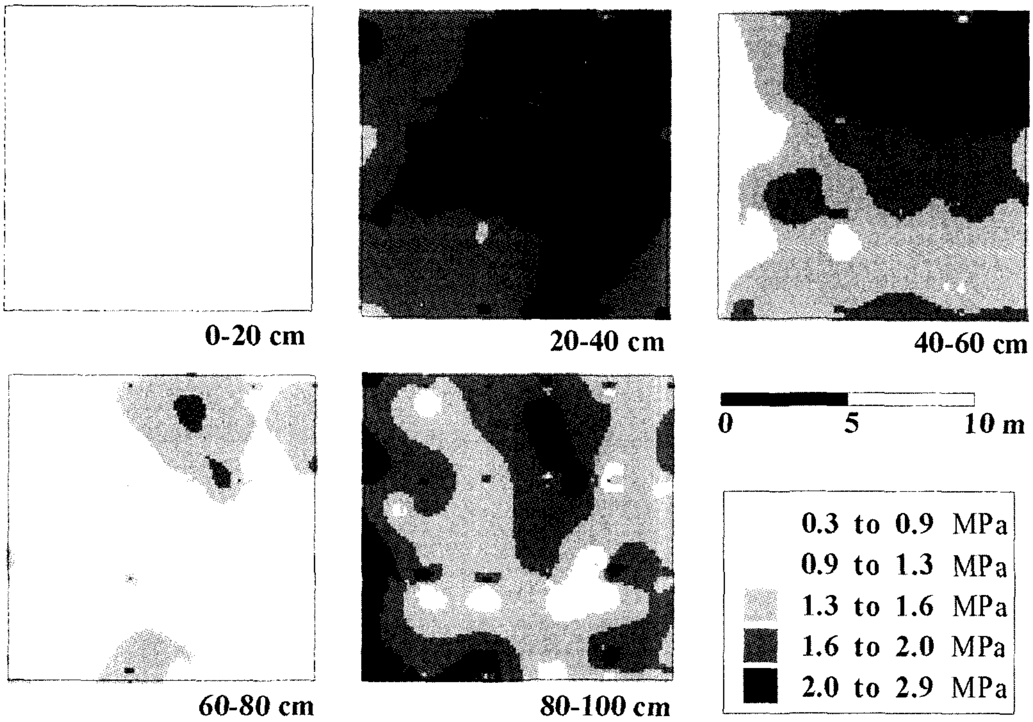


(b) Area C: high silt content

Fig. 7 Variograms of 20-cm-depth-averaged CIs in area B (a, top) and area C (b, bottom).



(a) B area: high clay content



(b) C area: high silt content

Fig. 8 Kriged 20-cm-depth-averaged CI maps for areas B (a, top) and C (b, bottom).

to the variogram, however, showed only one structure with a range less than 10 m, and did not capture the long-range structure.

Although variogram analysis of TD captured spatial structures with ranges less than 10 m, the distribution of semivariances was somewhat scattered and range of the structures was unclear, especially at small distances, possibly partly due to the anisotropic aspects of TD. Another cha-

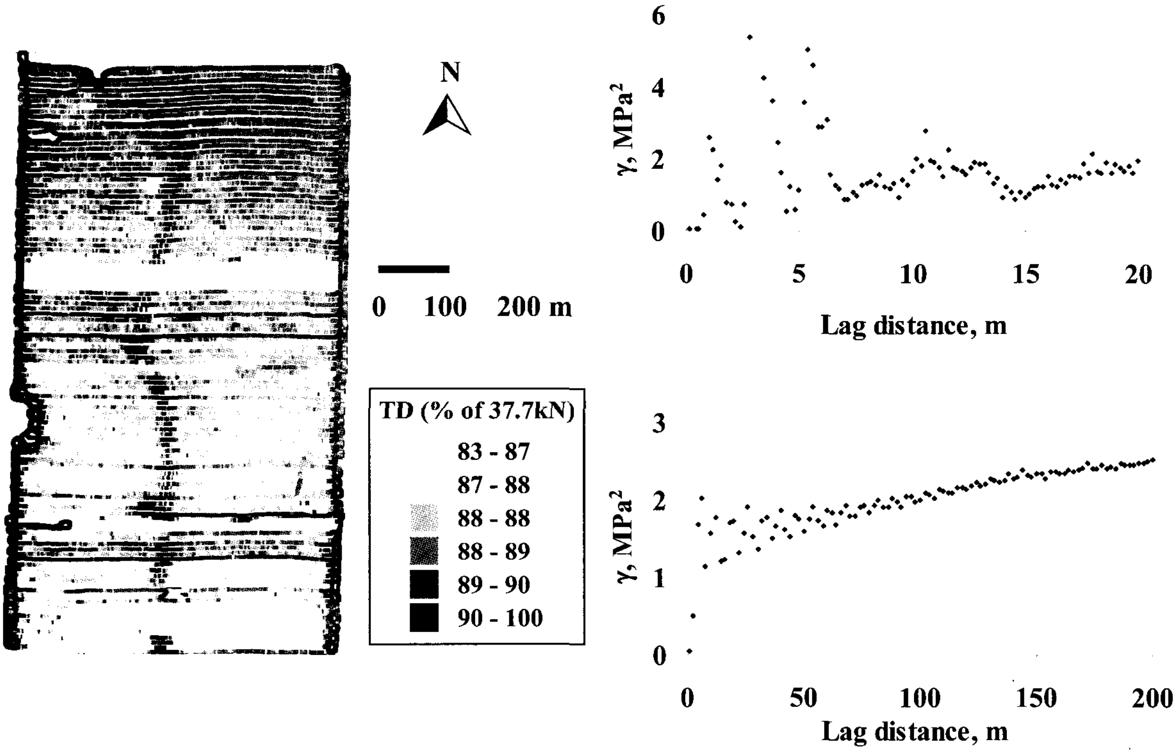


Fig. 9 Tillage draft map (left), and variograms at active lag distances of 20 m (right, top) and 200 m (right, bottom).

racteristic of the TD variograms was an abrupt increase in semivariance at smaller lag distances, indicating a large amount of nugget variance, or a noise component, in the TD. Possible reasons were: (1) TD smoothed the strength variability at small scales since it was an integrated value of soil strength over the operating depth and width of the tillage implement, (2) there was another spatial structure at lag distances smaller than the lag interval, which was 2 m for the variogram up to 20 m, and (3) there were measurement errors. An on-the-go soil strength profile sensor with multiple measurements along the depth and a higher sampling frequency would provide better quality soil strength data than TD for variogram analysis.

Conclusions

Two types of available soil strength data, cone index and tillage draft, were characterized using visual inspection, statistical methods, and variogram analysis. As a result of these analyses, important design parameters for an on-the-go soil strength sensor were established:

(1) Sensing depth, maximum soil strength, and sensing resolution were selected as 0.5 m, 10 MPa, and 0.1 MPa, respectively, based on the examination of CI profiles.

(2) Variability analyses of CI and TD indicated that the on-the-go soil strength sensor would require high-resolution, high-frequency measurements to capture the within-field variability in soil strength. If the sensor operates at a normal tillage speed of 2 m s^{-1}, the data acquisition frequency should be greater than 4 Hz to detect the 1- to 2-m repeating pattern observed in CI and TD data.

(3) Compaction level, depth, texture, and water content of the soil all significantly affected CI. The effects of these factors on data obtained with the soil strength sensor should be investigated through experiments.

Acknowledgments

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