International Journal of Natural and Engineering Sciences 5 (2): 19-25, 2011
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Study of the Effective Parameters of an On-the-go Single Blade Soil Mechanical Resistance Measurement System

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Received: January 29, 2011
Accepted: February 07, 2011

Abstract

An On-the-go Single Blade Soil Mechanical Resistance Measurement System (OSBSMR) was developed and tested under field conditions. The horizontal Soil Mechanical Resistance Index (SMRI) was obtained at discrete sensing depths nominally centered at 10, 20, 30 and 40 cm. Results showed that soil moisture content and working depth had significant effects on the SMRI. Increasing soil moisture content decreased both SMRI and soil cone index (CI). Travel speed in the range of 1.78 to 3.57 km h-1 didn't have significant effect on the SMRI. There was a good correlations with R^2=0.51 and R^2=0.69 between CI and SMRI at the depths of 20-30 and 30-40 cm, respectively, but this value in the depths of 0-10 and 10-20 cm were marginal. This was due to the SMRI depends on soil failure mode ahead the sensor as well as the degree of soil packing. A critical depth of 20 cm was obtained by surveying of soil failure mode.

Keywords: soil compaction sensor, data logger, profile meter, failure mode.

INTRODUCTION

The final yield of agricultural crops depends on the efficient parameters of growth stage. The soil physical conditions frequently have leading effect on crop yield as the controlling factor of ambient where the roots extend there. The main duty of soil related to plant growing is its mechanical support and also, providing nutrients, water, warmth and air requirements which relates to soil structure, intensively. Soil compaction is one of the important factors which damages the soil structure and results the limitation of root growth and development. Overall, the negative effects of soil compaction are frequently associated with a reduction in the availability and uptake of water and plant nutrients [14] resulting in a reduction in the crop yield. Surely, a range of soil compaction is required to ensure better contact between seeds and soil particles. Using subsoiler tool in the constant depth is a conventional approach to eliminate of hardpan problem. But in the some regions, the depth of repose and thickness of this layer has very variations even within one field [9, 11, 15, 16]. The depth of hardpan often is not given and in the some case, presence or not presence of the layer is uncertain in a field. Therefore, It may cause to the tillage operations are done either lower (not to eliminate the hardpan) or upper (to waste consumed power and energy and also, to upraise the poor soil of lower layer to the zone of root growth) than hardpan layer. Consequently, knowing variability in soil compaction within and across of an agricultural field causes to perform tillage operation according to the requirements of each region.

Assessment of soil compactness is accomplished by two main methods including measuring soil bulk density (direct method) and soil strength and/or mechanical resistance (indirect method). Laboratory determination of either soil compaction or soil strength at the spatial resolution needed in site-specific crop management (SSCM) is time-consuming, laborious, and expensive even if the required, spatially dense sampling is possible [6]. Assessment of soil strength is often performed by measuring the soil resistance to penetrometer probes [12]. Conventionally, a vertically operated cone penetrometer used for measuring soil mechanical resistance as an in-situ approach. But, cone penetrometer readings require a stop-and-go procedure with data collected at discrete locations [7] that is very time-consuming and tedious. On the other hand, understanding the spatial variability of soil strength requires the collection of extremely large amounts of data [9]. Therefore, using cone penetrometer is probably not a cost-effective process at large scale.

The difficulty of operation and mapping soil mechanical resistances by standard cone penetrometer [4] were motivated a number of researchers to look into alternative on-the-go sensing technologies.

Adamchuk et al. [1] designed and constructed a system with an array of strain gauges attached to the backside of a vertical smooth blade. The system was capable of estimating soil mechanical resistance at three depth intervals. The problem of this system, was a low ratio of signal to noise that effect on predicting soil mechanical resistance near the surface. Another prototype of the vertical blade equipped with an array of strain gauges was used to estimate a spatial pattern of soil resistance and to identify the trend of soil resistance changes with depth, assuming a linear change of resistance pressure with depth [2].

Sirjacobs et al. [18] developed and tested a sensor with thin blade that measured on-line soil strength variations at constant depth and speed in field conditions. The soil forces transferred to a transducer fixed on the machine that measured the draft force (F_x), the vertical force (F_z) and the moment (M_y). A significant relationship was found between CI and F_x and M_y measured by sensor (R^2=78%) and between gravimetric water content and the vertical force F_z (R^2=78%).

An on-the-go soil strength profile sensor (SSPS) was developed by Chung et al. [6]. The SSPS used multiple prismatic tips with a 60° apex angle and a base area of 361 mm², connected to a load cell array which extended horizontally in front of a main blade and spaced apart from each other. The extension and space of the tips was investigated and optimized through controlled tests. The ratio of Profile Soil Strength Index (PSSI) to CI was used to investigate the effect of extension and spacing of tips. In the other research Chung et al. [7] applied the verified sensor developed in their previous work [6] that had five prismatic force sensing tips on a 10 cm depth increment and extended 5.1cm from a main blade. They selected 1.5 m s^{-1} as a critical speed for in the field and 3.0 m s^{-1} in the soil bin. The repeatability and stability of the sensor was confirmed. They reported PSSI had higher values at locations with lower electrical conductivity (Ec_a) and water content, and higher bulk density values, also resulted that variability in PSSI was better explain when interactions among the soil variables were included as independent variables and when data were grouped into subset by depth and/or Ec_a level.

Chukwu and Bowers [5] developed a sensor which had three prismatic tips with a 30° apex angle and were extended 40 mm ahead of the shank and spaced 102 mm apart vertically. Results showed that the sensor measured well the differences in soil mechanical impedance with depth and location and these measurements correlated well with corresponding cone penetrometer measurements.

Hemmat et al. [13] studied on influence of failure mode induced by a single-tip horizontal penetrometer that used an S-shaped load cell housed inside a shank. The sensor was tested in a silt clay loam soil at three depths of 20, 25 and 30 cm, separately. Results showed that there was a significant relationship (R^2=0.75) between sensor measurements and CI when the sensing tip was operated below the critical depth; however this relationship wasn't significant as the sensing tip was moving through the disturbed soil and above the critical depth.

Siefken et al. [17] developed an instrumentation system with multiple blades capable of mapping soil mechanical resistance on the go at three depths simultaneously and evaluated the system performance. An acceptable correlation with R^2=0.76 were obtained between CI and multiple blades system measurements. Changes in travel speed, from 0.45 to 2.24 m s^{-1}, didn't have significant effect on the measurements of soil mechanical resistance.

The overall objective of this research was to design and develop of a sensor composed of a thin blade pulled in the soil which could take the measurements at multiple discrete depths simultaneously and continuously while traveling across the field. Specific objectives of this study were to:

1- Develop an on-the-go soil mechanical resistance profile sensor (OSBSMR) and test it at four depths (0-10, 10-20, 20-30 and 30-40), three forward speeds (1.8, 2.7 and 3.8 km h^{-1}) and two moisture content levels (approximately dry and wet).

2- Investigate the influence of operational parameters on horizontally on-the-go soil mechanical resistance measurements.

3- Investigate the effects of soil disturbance and the failure mode induced by sensor on horizontally on-the-go soil mechanical resistance measurements.

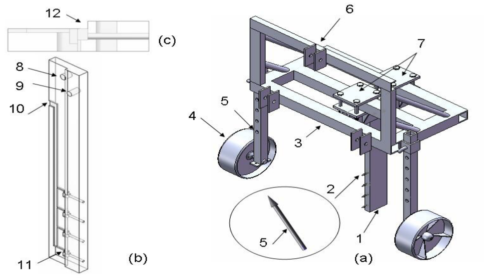

Figure 1. The photo of (a) OSBSMR (1. single blade, 2. conical rod, 3. chassis, 4. depth adjusting wheel, 5. depth adjusting bore, 6. Mechanism of three-point junction, to be conducted to middle rode of tractor, 7. the specific mechanism for junction of blade and chassis). (b) blade (8. the bore of axial pin, 9. the bore of shear bolt, 10. the channel of transiting load cell wires to data logger, 11. Load cell housing). (c) top view of blade (echelon of side surface of blade)

MATERIAL AND METHODS

Design and Fabrication

A horizontally on-the-go soil mechanical resistance profile sensor (OSBSMR) was designed to allow the simultaneous and continuous measurement of soil mechanical resistance at four depths, while moving across the field (Fig 1). The OSBSMR design comprises mechanical and electrical components. In mechanical part, it was notified to select and calculate the dimensions and material of blade, conical tips, connecting rods, chassis and characteristics of protective mechanism such that the blade could reliably penetrate in the soil up to a 40 cm depth. The lateral face of shank was fabricated in the special form such that allowed the load cells and their cables were conveniently located in it and didn't encounter to the probable shakes. The total length and width of the instrumented shank were 1000 mm and 150 mm, respectively. The thickness of shank was selected 40 mm to support the 20 mm wide of the load cells and to keep rigidity of the shank. In order to provide the desirable effective depth, a chassis was designed such that had necessary weight for the penetrating shank. Also, the chassis has two controling depth wheels which provide possibility of constancy and adjust of working depth.

Material of shank was one of the influence parameters in system design because of special operating conditions that included diverse factors as abrasion and impact. Thus in the construction of the sensor were used a ST37 steel ($S_y = 235\ Mpa$, $S_u = 320\ Mpa$ and $E = 207\ Gpa$) which were hardened up to a several centimeters thickness through special thermal operation. Consequently the steel achieved had desirable resistance against abrasion and impact. The conical tips were made of stainless steel which had a 128.67 mm² base area with 30° apex angle according to the ASAE standard [4]. The conical tips were unified to the rods and connected to the load cells by them. The connecting rods had an 8 mm diameter and a 108 mm length which passed through an oversized hole drilled in the shank. In order to prevent of soil entrance or other external materials into load cells housing, sealing washers were used. Also in order to protect the cables of the load cells a channel inside shank was contrived. By Solidworks Simulation software (Cosmoswork, 2007 SP0.0) stress analysis was done for the shank in order to reliable usage of the sensor in the field conditions. Also in order to confidence of non-bending in sets of rods and conical tips equation (1) was used:

$$F_{cr} = \pi^2 EI / L_e^2 \qquad L_e = 2L \quad (1)$$

Where,
F_{cr}: Critical force (N)
E: Steel modulus of elasticity (E= 207 GPa)
I: Moment of inertia (kg m^{-2})
L: Length of rod + height of conical tip (m)
By substituting the apparent values was obtained:
F_{cr} = 6.247 kN.

Assuming linear changes variation of soil resistance pressure against depth [1], the maximum pressure of 7MPa considered to the blade at highest operation depth. The sampling of soil mechanical resistance in the field by a standard cone penetrometer confirmed this result. Assuming coefficient reliability of 1.75, the maximum force exerted to the cones was calculated as equation (2):

$$F_{max} = n \times P \times A \quad (2)$$

Where,
F_{max} : Maximum force (N)
n: Coefficient reliability
P: Maximum pressure applied to the cones (MPa)
A: Base area of the cones (mm^2)

Substituting the apparent values, the value of F_{max} was calculated as 1.576 kN. Thus, there was no problem of bending because of $F_{max} \langle F_{cr}$.

To protect the sensor in the probable over-loads, a shear bolt mechanism was selected (Fig. 2). In order to calculate the resultant load exerted to the instrumented blade, the equation (3) was used:

$$F = P_{max}.D_{max}.t/2 \quad (3)$$

Where,
F: Resultant of spread load (N)
P_{max}: Maximum pressure acting on the end of blade (MPa)
D_{max}: Maximum operational depth (mm)
t: Thickness of blade (mm)

By substituting apparent values (D_{max} = 450 mm), resultant of spread load was calculated as F= 63 kN. The distance between the concentrate load and the end of the blade (L) is:

$$L = \frac{1}{3} \times 450 = 150 \text{ mm}$$

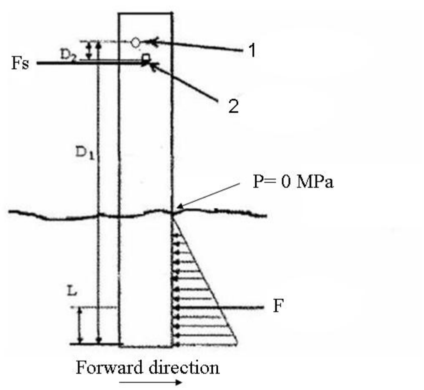

Figure 2. The schematic of the blade with applied loads 1- axial bolt, 2- shear bolt

By calculating the moment of the force of F about axial bolt, the shear force (F_s) acting on shear bolt was found by using the equation (4):

$$F_s = F \times (D_1 - L) / D_2 \quad (4)$$

Where,
D_1: Distance between the end of blade and axial bolt
D_2: Distance between axial bolt and shear bolt
By substituting apparent values, the shear force was calculated as F_s = 771.75 kN.

The moment force of weight was not calculated because of the negligible effect.

In order to select a shear bolt for instrumented shank, a shear bolt with 22mm diameter was selected, and then to control of proficiency of the mentioned bolt, the equation (5) was used:

$$\tau = \frac{F_s}{2A} \quad (5)$$

$$\tau = 771.75 \times 10^3 / (\pi \times 22^2) = 1015 \text{ MPa}$$

As the strength yield of such bolt is 1100 MPa, M22 bolt (Metric Thread) would function properly for this object. By assuming coefficient reliability, a bolt of M25 was selected to as axial bolt for connecting the blade to chassis.

The electronic section design consisted of selecting load cells and data acquisition system. As mentioned, the maximum expected force exerted to cones from soil is calculated about 1.58 kN. After a review of available commercial load cell products, a miniature load cell (Model CLS-2kNB, Tokyo Sokki Kenkyujo, Japan) with capacity of 2 kN and a external diameter of 20 mm was selected for this study. The load cell has a full bridge circuit of strain gages with compensated temperature range of -10°C to 60°C. Non-linearity, hysteresis and over load of the load cell were 0.5% RO, 0.5% RO and 150%, respectively. Calibration of load cells were performed by manufacture, but in order to obtain actual calibration values for operational ranges of expected mechanical resistances and to confide of linear behavior of load cells, laboratory calibration was performed by tensile-compression device of STM-20 Model. (Santam Company).

Field experiments and data collection

Field experiments were conducted at research farm of faculty of agriculture, Ardabil, Iran on silt loam soil (with 6% clay, 69% silt and 25% sand). The experiment was conducted within a field where for two years wasn't ploughed and had some alfalfa residues.

The measurement system mounted on the three point hitch of a tractor was pulled along 36 paths of a 25 m length in the field with inter-distance of about 5m. The blade depth was adjusted to 45 cm using the hitch position control system and controlling depth wheels. The soil mechanical resistance force was transmitted to the load cells through cones and connecting rods and then four sets of load cell measured the soil mechanical strength forces through a DT800 data logger (dataTaker Co., UK). The data transmitted to a laptop computer placed on the tractor cabin for data processing and saving. The output of the miniature load cells were 1.5 mV V^{-1} at full capacity (2 kN). The tractor's battery was used to excitation input, resulting in a 36 mV V^{-1} signal at 2 kN. In this study SMRI was introduced as horizontally soil mechanical resistance index measured by OSBSMR which was calculated by dividing of the force to the cross sectional area of one cone (128.67 mm^2)

Figure 3. The tractor-mounted soil cone penetrometer for collecting cone index data in the experiment

A tractor-mounted soil cone penetrometer with multiple-adjustable probes and with capability for determining of cone index values in crop rows was used for cone index measurements [3]. This device composed of mechanical, electrical and hydraulic sections that can evaluate soil strength condition at 0-45cm soil depth (Fig. 3). The mechanical section was comprised a frame to support other sections of unit and the three-point hitch, for attachment to the tractor. The hydraulic power was used for inserting force of probes in soil.

By using DT800 data logger (dataTaker Co., UK), the obtained force and depth data from the relative sensors, were collected and sent to the laptop computer for displaying of cone index-depth curve and saving. The tractor-mounted soil cone penetrometer measurements was obtained before beginning of OSBSMR measurements such that it collected the data near the path appointed to sensor (0.5 m).

Experiments were laid out in completely randomized design with a factorial arrangement of treatment and three replications. The treatments included two soil moisture conditions (dry and irrigated), and three levels of travel speed (1.78, 2.67 and 3.57 km h^{-1}). In this study, the effect of two levels of moisture content of relatively dry and field capacity and also four levels of depth from 0-40cm depth and three levels of forward speed of 1.78, 2.67 and 3.57 km h^{-1} were investigated as independent variables on the soil mechanical resistance. Duncan's Multiple Range test was used for the mean comparison of all tests.

First level of moisture content was non-irrigated (dry) condition and another level was irrigated condition so that the soil moisture content was reached near the field capacity. The sampling of soil was conducted to determining moisture content and bulk density using the auger which was taken to the depth of 40 cm with 10 cm intervals.

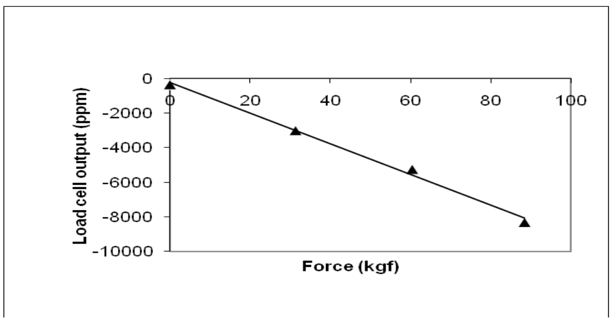

Figure 4. Results of test of linear behavior of load cell 1 with R^2= 0.994 from laboratory test.

In order to determine moisture content and bulk density measurements were taken on 10cm depth increment. Also, a profile meter was used for evaluation of soil failure mode.

RESULTS AND DISCUSSIONS

Fig. 4 shows the linear response of the load cell 1 (used for soil strength measurement of 0-10 cm soil depth) for semi-static forces when has been not installed inside the instrumented blade. The regression line provided the calibration coefficients. The primary tests of load cells performed in laboratory by static loading. It indicated the proper response of the sensors.

Effect of Soil Moisture Content on Soil Mechanical Resistance Index (SMRI)

Results showed increasing soil moisture content from dry condition to wet condition resulted in a decrease in the average of soil mechanical resistance about 2.8 times. Similar results were obtained in other studies as Voorhees and Walker [19], Chung et al. [6] and Sirjacobs et al. [18]. The reason of this relationship could be attributed to decrease in the angle of soil internal friction which causes to lower soil resistance against external forces. Further reason relates to decrease the friction between soil and cones surfaces resulting convenient penetration of cones through soil.

Effect of working depth on SMRI

A significant relationship ($P< 0.01$) was observed between working depth and SMRI. This relationship could be explained by equation (6):

$$SMRI\,(MPa) = -0.362 + 0.075d\,(cm),\ R^2 = 0.923 \qquad (6)$$

Where d is the depth of operation.

Fig. 5 shows with increasing the working depth, the mean values of SMRI increased significantly. All levels of depth were significant on SMRI. In the depth of 40 cm, the mean values of SMRI had highest value. This due to vertical forces applied to soil surface usually transmit and distribute toward lower layers of soil and also in the higher depth, the parameter of weight has important role in increasing soil mechanical resistance.

Effect of Forward Speed on SMRI

Although, minimum and maximum value SMRI have occurred in the forward speed of 2.68 and 1.78 km h^{-1}, respectively, these differences weren't significant statistically (Fig. 6). Other researchers who applied same range of forward speed obtained similar results [7, 17].

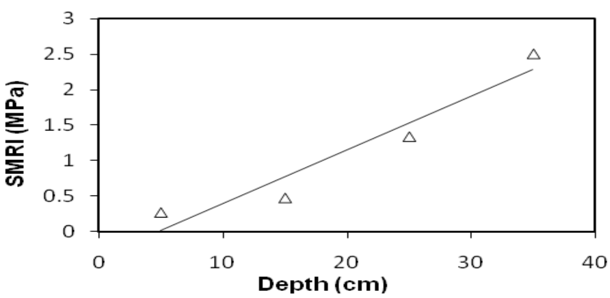

Figure 5. Effect of working depth on mean values of SMRI (The values of Y axis is the mean of SMRI for both moisture levels)

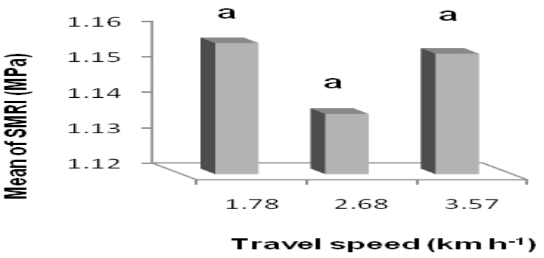

Figure 6. Effect of forward speed on mean value of SMRI (SMRI values relate to the mean for both moisture levels)

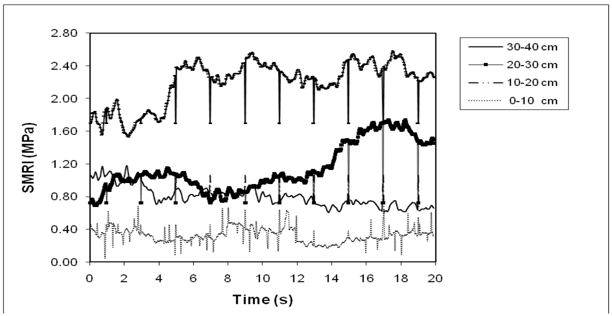

Figure 7. The fluctuations obtained from SMRI versus time at four depths.

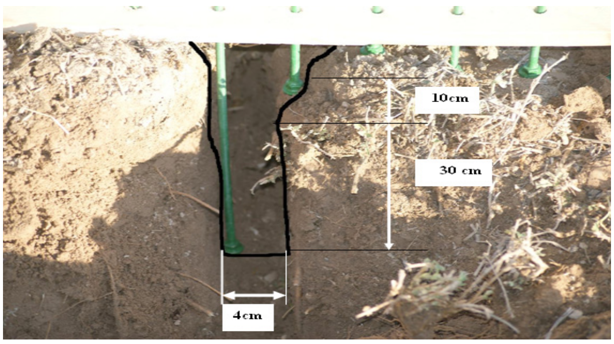

Figure 8. The cross sectional of soil disturbance perpendicular to the direction of forward speed by the OSBSMR

Fluctuation of Sampling

Fig. 7 represents the relationship between SMRI and time period of one of the path of experiment (20 s). At the 0-10 and 10-20cm soil depths, the amount of noise signals is higher than the 20-30 and 30-40cm depths at some parts of time. It was caused by presence of a lot of clods and stones in these depths. Overall, the spikes in the signal were due to the impact of the cones and the clods, stones and also presence of pores and free spaces within soil. At the 0-10cm and 10-20cm depths, the SMRI has much lower values. This was due to arising soil over the blade and manipulating of soil by it. The coefficient of variation obtained from analysis of variance was 12.61%.

Comparison of SMRI and CI

An analysis of linear regression was conducted to evaluate of correlation between SMRI and CI. Table 1 shows the results. As appeared, at 0-10 and 10-20 cm depths, the correlation between SMRI and CI is very low (R^2=0.23 and R^2=0.16$_2$ respectively). This low relationship means that in these depths, there was intense disturbance in the soil. But at the depths of 20-30 and 30-40 cm, this relationship was good (R^2=0.51 and R^2=0.69$_2$ respectively). This can be explained by the failure mode made in the soil. Fig. 8 shows the cross sectional soil disturbance perpendicular to the direction of forward speed by the OSBSMR.

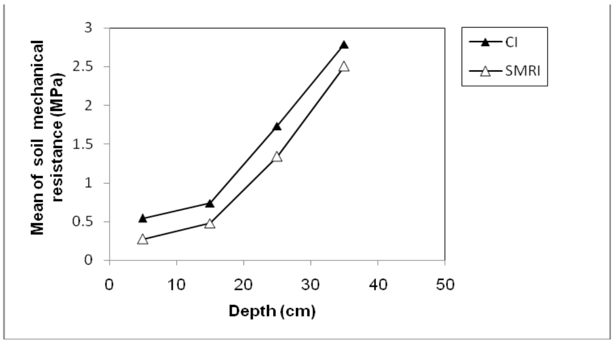

Figure 9 . Measurement results from tractor mounted cone penetrometer and OSBSMR versus depths.

According to Godwin and Spoor [10], in the near of the soil surface, where soil encountered with tillage instrument displaced forwards, soil failure mode for tine blade is sideways and upwards. This type was known as crescent failure type. At the depths of higher than critical depth, soil shifts sideways and forwards that was known as lateral failure mode (or bearing-capacity type failure). As seen in Fig. 8, the failure mode of soil at the 0-20cm depth is crescent type and thus, there are most disturbances in the soil. But at the 20-40cm depth, there is low disturbance in the soil and type of the failure mode is lateral type failure. While the soil failure mode in the head of a vertically operating cone penetrometer is always bearing-capacity type failure [8] and thus at the 20-40 cm depth due to produce similar failure mode between OSBSMR and penetrometer was obtained stronger correlation in the soil mechanical resistance.

Fig. 9 shows the mean of CI and SMRI values versus depth. It was found that in both cases the trend of soil mechanical resistance values is similar. Moreover, mean values of SMRI are lower than CI values that were primarily due to different direction of movement. The possible interaction between main blade and soil resulted in arising soil over blade. This can be caused to measure the mechanical resistance of manipulated soil instead intact soil that is certainly lower than true value.

Attending to the trend of both indices indicates that near to the depth of 20cm the diagrams were encountered by an ascendant slope. This can be explained by presence of plow pan or location of conventional tillage depth at this depth. Diagram of CI versus depth represented in Fig. 10 indicates presence of hardpan at about 40cm depth. The coefficient of variation of the data obtained by OSBSMR was 12.61 whereas this value for tractor-mounted cone penetrometer was 8.61. Therefore, amount of fluctuation of SMRI is higher than CI.

Table 1. The coefficients of correlation between SMRI and CI.

	Working depth (cm)			
	0-10	10-20	20-30	30-40
R^2	0.23	0.16	0.51	0.69

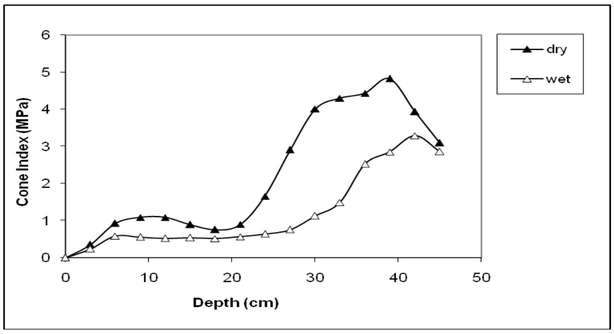

Figure 10. The diagram of CI versus depth for utilizing hardpan depth.

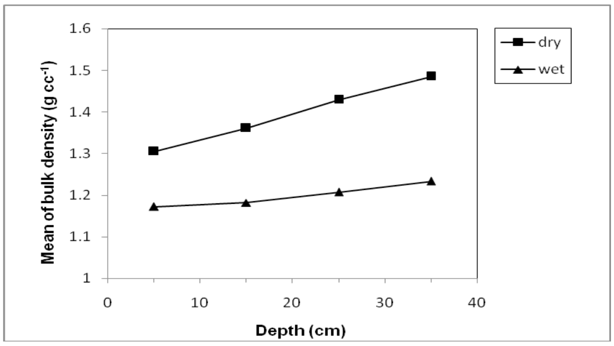

Figure 11. The diagram of bulk density versus operating depth

Bulk Density

Bulk density is one of the direct approaches to measure of soil strength. Results of analysis of variance showed that the effect of operating depth and moisture content on bulk density were significant as SMRI. Regression results showed similar trend for both bulk density and SMRI with increasing depth ($P<0.05$). The diagram of bulk density in two moisture content conditions was shown in Fig. 11. With increasing operational depth, bulk density in both levels of moisture trended to increase. At relatively dry condition, the bulk density has higher values compared to field capacity condition. Also, increase of bulk density at the field capacity condition was lower than relatively dry condition. This may be attributed to the soil's pores that were saturated with water at the field capacity condition. This caused to the components of soil couldn't approach together because water is assumed a non-compactable liquid.

CONCLUSIONS

Knowledge of variability in soil strength within an agricultural field provides the purpose of precision agricultural conception by operating tillage according to requirement of each region. In this study one prototype of a horizontally on-the-go soil mechanical resistance profile sensor (OSBSMR) was developed and evaluated in field conditions that provided measurements continuously while traveling across the field.

The following conclusions were drawn from the results of this study:

1- The OSBSMR was sensitive enough to recognize small changes in soil mechanical resistance due to changes in soil water content and operational depth.

2- Changes of travel speed from 1.78 to 3.57 km h^{-1} didn't have significant effect on the horizontal soil mechanical strength values. Thus, for speedy operation was suggested to use of a 3.57 km h^{-1} travel speed was suggested.

3- The failure mode of soil forward of the sensor in the depth of 0-20 cm was crescent failure type that differed from tractor mounted cone penetrometere. But it was bearing capacity type at the depth of 20-40 cm as cone penetrometere thus at these depths was obtained strong coefficient of correlation between SMRI and CI values.

4- The presence of instantaneous variables within soil, as clods, stone, pores and free spaces causes to produce the fluctuations in the sensor measurements.

5- Experiment results showed that the presence of plow pan at about 20 cm depth and hardpan at about 40 cm depth.

6- Using OSBSMR for measuring soil mechanical resistance represented the variability of soil strength within a field better than bulk density measurements.

7- The relationship between SMRI and CI were good when those were operated below the critical depth.

REFERENCES

[1] Adamchuk VI, Morgan MT, Sumali H. 2000. Application of a strain gauge array to estimate soil mechanical impedance on-the-go. Transactions of the ASAE. 44 (6): 1377–1383.

[2] Adamchuk VI, Morgan MT, Sumali H. 2001a. Mapping of spatial and vertical variation of soil mechanical resistance using a linear pressure model. Paper No. 01-1019, ASAE, St. Joseph, Michigan.

[3] Ahani M, Abbaspour-Gilandeh Y, Askari Asli-Ardeh E, Rasooli Sharabiani V. 2009. Design and performance of a tractor-mounted soil cone penetrometer with multiple-adjustable-probe. International Agricultural Engineering Conference, Bangkok, Thailand, 7-10 December.

[4] ASAE Standards, 52th Edition (2005), S313.2. Soil cone penetrometere. St. Joseph, Michigan, ASAE.

[5] Chukwu CG, Bowers Jr. 2005. Instantaneous multiple-depth soil mechanical impedance sensing from a moving vehicle. ASAE Paper. No. 971077.

[6] Chung SO, Sudduth KA, Hummel JW. 2003. On-the-go soil strength profile sensor using a load cell array. ASAE Paper. No. 031071. St. Joseph, Mich.: ASAE.

[7] Chung SO, Sudduth KA, Plouffe C, Kitchen NR. 2004. Evaluation of an on-the-go soil strength profile sensor using soil bin and field data. ASAE/CSAE meeting presentation. No. 041039.

[8] Chung SO, Sudduth KA. 2006. Soil failure models for vertically operating and horizontally operating strength sensors. Trans. ASABE. 49: 851–863.

[9] Clark RL. 1999. Soil strength variability within fields. In: Precision Agriculture '99: Papers Presented at the 2nd European Conference on Precision Agriculture, edited by J. V. Stafford (Sheffield Academic Press, Sheffield, UK). pp. 201–210.

[10] Godwin RJ, Spoor G. 1977. Soil Failure with narrow tines. J. Agric. Engng Res. 22(3): 213-228.

[11] Gorucu S, Khalilian A, Han YJ, Dodd RB, Keskin M. 2001.Variable depth tillage based on geo-referenced soil compaction data in coastal plain region of South Carolina. ASAE Annual International Meeting. No. 01-1016, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

[12] Hanquet B, Sirjacobs D, Destain M. 2004. Analysis of soil Variability measured with a soil strength sensor. Precision Agriculture. 5: 227-246.

[13] Hemmat A, KHorsandy A, Masoumi AA, Adamchuk VI. 2009. Influence of failure mode induced by a horizontally operated single-tip penetrometer on measured soil resistance. Soil & Tillage Research. Still-2672.
[14] Motavalli PP, Stevens WE, Hartwig G. 2003. Remediation of sub-soil compaction effects on corn N availability by deep tillage and application of poultry manure in a sandy-texturerd soil. Soil Till. Res. 71(2):121-131.
[15] Raper RL. 1999. Site-specific tillage for site-specific compaction: is there a need? Proceedings of the International Conference of Dryland Conservation/Zone Tillage, Beijing, China.
[16] Raper RL. 2005. Subsoiler shapes for site-specific tillage. Applied Engineering in Agriculture. 21(1): 25-30.
[17] Siefkin RJ, Adamchuk VI, Eisenhauer DE, Bashford LL. 2005. Mapping soil mechanical resistance with a multiple blade system. ASAE Paper. 21(1): 15-23.
[18] Sirjacobs D, Hanquet B, Lebeau F, Destain MF. 2002. On-line soil mechanical resistance mapping and correlation with soil physical properties for precision agriculture. Soil Till. Res. 64(3-4): 231-242.
[19] Voorhees ML, Walker PN.1977. Traction ability as a function of soil moisture. Transactions of the ASAE. 20(5): 806-809.