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Design, construction and field evaluation of a multiple blade soil mechanical resistance sensor

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ABSTRACT

A multiple blade soil mechanical resistance sensor (SMRS) that could measure soil mechanical resistance index (SMRI) continuously at four depths was designed, constructed and tested in two field conditions. Results showed that the effects of soil moisture content and depth on SMRI were significant ($P < 0.01$) while the effect of travel speed ranging from 1.78 to 3.57 km h^{-1} on SMRI was not significant. Comparison between SMRI and tractor-mounted soil cone Penetrometer measurements (CI) indicated that the coefficient of variation of SMRI was lower than CI. Also, there were good correlations between SMRI and CI at the depths of 10–20, 20–30 and 30–40 cm with the coefficient of determination (R^2) of 0.84, 0.83 and 0.80, respectively due to same failure mode between the two systems. Lower correlation obtained at the depth of 0–10 cm ($R^2 = 0.63$) was due to the difference between the failure mode of SMRS (crescent mode) and tractor-mounted cone penetrometer (bearing-capacity). Low soil disturbance, high correlation with CI and low oscillations in measurement are some advantages of SMRS.

1. Introduction

Soil physical conditions have a large effect on crop yield. The main duty of soil in relation to plant growth is to support mechanically and provide nutrients, water, heat and air requirements which greatly relates to the soil structure. One of the main effective factors which causes the collapse of soil structure is soil compaction. The negative effects of soil compaction are frequently associated with a reduction in the availability and uptake of water and plant nutrients (Motavalli and Stevens, 2003) which can be resulting yield decline. A hardpan in agricultural soil due to frequent traffic and similar depth tillage also limits root growth. If the depth of this layer in a field is known, tillage carries out at an appropriate depth to eliminate this hardpan.

A direct approach to evaluate soil compaction is via measuring soil strength. Consequently, knowing variability in soil strength within and across an agricultural field will allow performing tillage operations, according to the requirements of each region (Rahimi-Ajdadi et al., 2011). Soil strength has been traditionally measured by means of standard cone penetrometer (ASAE Standards, 2005) with its measurements carried out whilst stationary. However, understanding the spatial variability of soil strength requires the collection of extremely large amounts of data, which is probably not a cost-effective process at large scale (Clark, 1999). In order to overcome this limitation and obtain efficient data collection, horizontal on-the-go soil compaction sensors were tested by several research groups who generated soil compaction maps using Global Positioning System (GPS) data. On-the-go mapping of soil mechanical resistance can be accomplished through continuous logging of geo-referenced measurements with a sensor across a field (Adamchuk et al., 2006). Emergence of new technologies in manufacturing electronic sensors is allowed considerable evolution in this area.

Alihamsiah et al. (1990) fabricated the first horizontally soil mechanical sensor (Hemmat et al., 2009) and evaluated the effects of tip geometry, extension apex angle and forward speed on the measurement of the soil mechanical resistance. The sensor constructed by Chukwu and Bowers (2005) was similar to the sensor developed by Alihamsiah et al. (1990). This three-depth soil

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mechanical resistance sensor was compared with a Delmi penetrometer and they obtained a good correlation with $R^2 = 0.76$.

Andrade et al. (2001) showed that soil cutting force was a function of soil bulk density, moisture content and the location of the cutting elements within the soil profile. Andrade et al. (2004) developed an advanced version of the sensor made by Andrade et al. (2001) with a shank width of 27 mm and a 90° rake angle which was more compact and less expensive. Sirjacobs et al. (2002) made a sensor constituted of a thin blade pulled into the soil at constant depth which was held by a transducer for measuring the draft force (F_x), the vertical force (F_z) and the moment (M_y). The conclusions obtained from their study were validated by Hanquet et al. (2004).

Chung et al. (2003) designed and fabricated an on-the-go soil strength profile sensor that measured soil force using a load cell array. Each force-sensing tip was connected to a load cell located inside a narrow soil-cutting blade with tips extending in front of the blade. Results indicated that the mechanical resistance was higher at locations with greater bulk density, lower electrical conductivity and water content (Chung et al., 2004). A similar system was fabricated by Rahimi-Ajdadi et al. (2011) whose results showed that the multiple probe sensor represented closer data to cone penetrometer with a correlation coefficient of 0.83 in the depth between 20 and 40 cm due to the same failure mode between the multiple probes sensor and cone penetrometer. Again the force-sensing tip was connected to a load cell located inside a narrow soil-cutting blade and the tips extended in front of the blade edge. The main blade was mounted to a frame using a shear bolt mechanism and the frame was attached to a tractor 3-point hitch. Multiple prismatic tips mounted on a main blade extended from the leading blade edge and were spaced apart at a distance of 50 mm to minimize interference from the main blade and adjacent sensing tips.

The influence of failure mode induced by a single-tip sensor was investigated by Hemmat et al. (2009). They obtained a significant relationship ($R^2 = 75\%$) between data obtained from an on-the-go soil mechanical resistance sensor and a cone penetrometer for the depth of 30 cm as the formation of the same failure modes existed whereas for shallower depths the relationship was not significant as there were different failure modes between the sensor and cone penetrometer.

Siefkin et al. (2005) fabricated and tested a multiple blade system which was used for mapping soil mechanical resistance at three depths. They reported that all three sets of maps, including soil mechanical resistance and electrical conductivity suggested strong spatial similarities. They did not have a good statistical correlation because of sections with contradictive data within the field.

Adamchuk et al. (2006) Compared to sensors for measuring soil mechanical resistance, including a vertical blade with a strain gauge array above the soil surface and a sensor with five prismatic horizontal sensing tips providing resistance data at discrete depths. Their results showed that there was a marginal correlation ($R^2 = 0.32$–0.46 for average soil mechanical resistance estimates) between each of these two sensors and a cone penetrometer while estimates from the two sensors were more strongly related to one another.

The main challenge facing the most developed systems which used from single blade with multiple tips to measure soil mechanical resistance were interaction of the sensor outputs such that the measurements of lower tips affect the higher tips and also excessive soil disturbance which results in the output data from the higher sensors having lower values compared to actual values. Some other limitations of these sensor systems were single depth measurement and low signal-to-noise ratio (Siefkin et al., 2005).

Therefore the objectives of this study were to:

1. Design and construct a multiple blade system to measure soil mechanical resistance on-the-go at four depths simultaneously.
2. Evaluate of measurement system in two field conditions.
3. Investigate the type of failure mode generated by a horizontal multiple blade system compared to a tractor-mounted soil cone penetrometer constructed by Ahani et al. (2009).

2. Material and methods

2.1. Design and instrumentation

The main design principle of the multiple blade soil mechanical resistance system (SMRS) was to use a larger surface against which the soil force was applied rather than a small cone or prism in order that the local variables in soil like stones and cavities will be minimized.

The SMRS design consisted of two parts. Firstly, the mechanical part was comprised of multiple blades with unequal lengths each equipped with a transducer, chassis and safety mechanism. Secondary, the electrical part which consisted of transducers, data acquisition system and signal processing. The blades were made from CK45 steel and were designed to be pulled at a perpendicular rake angle to the soil surface. Since the most pressure was endured by the blade operating at the greater depth, its design was analyzed. The wedge angle was selected to be 60° for the sensing tool to reduce soil disturbance, avoid extreme force measurements and soil uprising. The blade thickness matched the dimension of the force transducer of 25 mm. A schematic of the SMRS as well as the photo of one of its blades are presented in Fig. 1. Four blades of measuring system were attached on a chassis which mounted to the three-point hitch of a tractor and a shear pin was used as a safety overload mechanism. A circular tube cable protector was used in the rear of the shanks to prevent damage to the strain gauge cables.

Fig. 2 shows a schematic of the measuring mechanism of the SMRS. The measuring mechanism design was based on sensing the

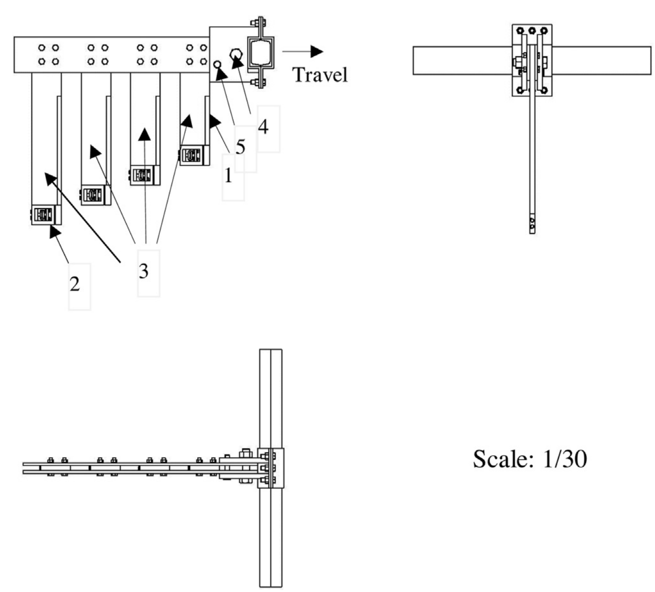

Fig. 1. Schematic of the multiple blades soil mechanical resistance sensor (SMRS) including: (1) wedge part; (2) sensing unit; (3) instrumented blades; (4) pivot bolt and (5) shear bolt.