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Development and field testing of an integrated sensor for on-the-go measurement of soil mechanical resistance

A. Hemmat[a,*], A.R. Binandeh[a], J. Ghaisari[b], A. Khorsandi[a]

[a] Department of Agricultural Machinery Engineering, College of Agriculture, Isfahan University of Technology, Isfahan 84146-83111, Iran
[b] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84146-83111, Iran

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ABSTRACT

Within-field variability of soil physical and chemical properties is generally regarded as the main causes contributing to variability in crop yield. High soil strength due to soil compaction has been recognized as an important negative factor in crop growth and yield. Measurement of soil strength is a common indirect measure of soil compaction. In this research, an integrated sensor – consisted of vertical and horizontal sensors – was developed and evaluated. The vertical sensor was a 60-cm diameter instrumented disk coulter with an ultrasonic distance sensor for measuring the penetrating depth of the coulter into the topsoil layer in a depth range of 0–20 cm. For measuring the soil mechanical resistance at two discrete depths (20 and 30 cm), a horizontal penetrometer with two 30° prismatic tips was integrated with the disk coulter. The integrated sensor was tested in a field with silty clay loam soil and at two gravimetric water contents (WCs) of 6 (low) and 13.5% (medium) in three replications. At the time of testing, standard soil cone penetrometer measurements along the same transects were also taken and the cone index (CI) was calculated. The results showed that the penetrating depth of the disk coulter was sensitive to changes in surface soil strength. At low WC, the measured horizontal soil resistance index (HRI) at each depth with/without vertical sensor was the same and therefore its value was independent of soil failure induced by the disk coulter ahead of the prismatic tips. However, at medium WC, due to deep penetration of the disk coulter and thus, probably reduction of geostatic pressure, the measured HRI at the depth of 20 cm with vertical sensor was decreased. To minimize the interaction of the coulter-induced failure zone with the upper tip, it is suggested that to install the disk coulter in offset position relative to the shank of the horizontal penetrometer. A significant negative linear relation between the operating depth of the disk coulter and the CI was found. Also, the relationships between the HRI and CI at both depths were significantly linear. Therefore, with offset positioning the sensors on the frame, the developed integrated sensor could be used to map the mechanical resistance of a soil profile to a depth of 30 cm.

1. Introduction

The continuing trend toward the use of larger and heavier equipment for greater productivity increases the risk of soil compaction. Soil compaction is a densification and reduction in porosity, associated with changes to the soil structure, leading to an increase in strength and a reduction in hydraulic conductivity [1]. Excessive soil compaction has negative effects for agriculture and the environment. Soil compaction reduces infiltration, water storage, aeration, drainage, rooting, and crop growth [2], while increases runoff and soil erosion, accelerates potential pollution of surface water by organic waste and applied agrochemicals [3].

Soil strength, or mechanical resistance to failure, has been widely used to estimate the degree of soil compactness. Two approaches have been used to obtain spatial variations in soil mechanical resistance at the field scale: (1) stop-and-go method (standard cone penetrometry) and (2) on-the-go soil sensors [4]. Measurement of soil mechanical resistance by a cone penetrometer is basically a stop-and-go insertion method which is not fast enough to obtain enough data in intensive sampling situations. Therefore, it is a time consuming and labor intensive method. However, on-the-go soil sensors can be used to map the soil compaction by measuring spatially continuous estimates of the soil strength, for (a) mapping the general compaction in a specified soil layer by measuring the draft (bulk strength sensor) or vertical force of a reference tool and (b) sensing soil strength profiles throughout an agricultural field which typically involves either tip-based or tine-based soil sensors [4].

Tillage tool has been used as a bulk strength sensor and measurement of its draft was suggested as a surrogate variable for continuous mapping of soil strength. However, Mouazen and Roman [5] could not observe any clear correlation between

* Corresponding author. Tel.: +98 311 391 3493; fax: +98 311 391 3501.
E-mail address: ahemmat@cc.iut.ac.ir (A. Hemmat).

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measured draft and soil dry bulk density or soil moisture. They suspected that draft was not a proper measure to indicate soil compaction while ignoring other influencing factors, such as: soil type, moisture, and working depth. Hall and Raper [6] also stated that draft alone is not a good indicator of soil conditions, because different soils may have the same mean draft, but present different physical conditions [7,8].

The most common soil strength profile sensor is tip-based soil sensor [4]. A horizontally operated tip-based soil mechanical resistance sensor acts as a rigid tine [9]. Stafford [10] identified two modes of soil failures caused by a rigid tine: brittle and plastic flow (compressive) failure. Godwin and Spoor [11] referred to these failure types as crescent and lateral failure. The depth at which the soil failure mode changes from brittle to compressive is called the critical depth (dc). Experimental observations [11,12] indicated that change in failure mode occurs at working depth/tine width ratio, termed aspect ratio, around 6 (for soils in friable state) or higher. In addition to the aspect ratio, the critical depth depends on soil type [13], soil water content and bulk density, surface soil surcharge, operating speed [14] and rake angle of the tine [11]. Soil disturbance is assessed by direct excavation. To observe the failure mode and to locate the critical depth, profile trenches should be opened up perpendicular to the direction of operation [11].

For on-the-go mapping of spatial variability in soil compaction, single- and multiple-tip horizontal sensors have been developed and field tested [15–23] to measure the soil mechanical resistance. However, the interaction between soil and the sensing tips in terms of the failure mode was not reported. It have been recently reported [4,9,24] that the measured soil resistance in different soil layers not only depends on the degree of soil compaction but also depends on soil failure mode induced by the shank of the sensor. Hemmat et al. [24] developed a single tip horizontal soil mechanical resistance sensor and measured the soil mechanical resistance as well as observed the failure mode in front of it while the sensor tip working at three different depths of 20, 25 and 30 cm. They observed that the sensor tip was in disturbed soil while working at 20 or 25 cm deep, whereas for 30-cm working depth the tip was confined in undisturbed soil. They reported that the critical depth was around 24–25 cm deep (see Fig. 8 in reference [24]). Their results showed that average horizontal soil mechanical resistance index (HRI) values for both depths of 20 and 25 cm were similar due to the brittle failure mode in both cases. However, when the tip was operated below the critical depth of the sensor, the value of HRI at 30 cm depth increased three times when compared with 20 or 25 cm depth values. This was due to change in failure mode from brittle to compressive mode below the critical depth. There was a significant relationship ($R^2 = 0.75$) between HRI and the cone index (CI) measured with a vertically operated cone penetrometer for the 30-cm depth, whereas for shallower depths the relation was not significant. This was explained due to the fact that the soil failure near the surface was of a three-dimensional crescent type. As the sensing tip was moving through the disturbed soil (crescent failure), it registered the resistance forces mostly arising from the parasitic (frictional and adhesive) forces that develop at an interface between the tip surface and the surrounding soil. On the other hand, the soil failure mode in front of a cone of a vertically operated penetrometer is of a bearing-capacity type [17]. The soil failure mode ahead of the tip of the horizontally operated sensor located below the critical depth is also a bearing-capacity type. The results of their research show that the correlation between measurements obtained with the vertically and horizontally operated penetrometers would be significant as long as both produced the same soil failure mode.

One approach to obtain a significant correlation between the output of a soil sensor and the cone index measured near the ground surface (the zone above the critical depth for either the tip-based or tine-based soil sensors, i.e., an upper failure zone where the soil displacement has forward, sideways, and upward components (crescent failure, [11]) is to use the changes in operating depth of a disk coulter (a very narrow tine) or the vertical impedance force applied to it. These methods were used by some researchers [25,26]. Hemmat et al. [25] developed a 76.2-cm diameter instrumented disk coulter with two depth-measuring sensors (rotary potentiometer and ultrasonic proximity sensor) along with a global positioning system (GPS) receiver to geo-reference operating depth measurements. The results showed that the depth measured with the ultrasonic sensor had significant correlation with average CI of the soil surface layer. For a backward raked narrow tine such as a disk coulter, the bearing-capacity type soil failure starts near the surface. Even for the concave disks with a zero sweep angle (i.e. the face of the disk is parallel to the direction of travel), all the soil reaction is of the scrubbing form. The scrubbing component is compressive in nature and always produces an upward vertical force. The force was estimated by Godwin et al. [27] using the bearing capacity theory. Instrumented oscillating disk coulter was also used to measure soil mechanical resistance. Pitlal et al. [26] developed a soil coulterometer as an “on-the-go” electro-mechanical system to collect both horizontal and vertical impedance force data at multiple depths of 100 mm and 305 mm using an oscillating coulter. They collected data from a typical central Kentucky field along four passes. Standard cone penetrometer measurements were taken for each pass between the same depth ranges using a multi-probe soil cone penetrometer. Soil bulk density and water content measurements between depths of 100 mm and 305 mm in steps of 50 mm were taken for each pass using a nuclear soil moisture/density gauge. Simple linear regression analysis was used to find the relationship between coulter indices (kN m^{-1}), cone index (MPa), dry soil bulk density (Mg m^{-3}) and water content (%). Coefficients of determination (R^2) as high as 0.996 were obtained between coulter indices and dry soil bulk density measurements and 0.998 for coulter indices and water content measurements.

The overall objective of the research reported here was to develop an integrated soil mechanical resistance sensor to measure the variations in soil strength within a 30 cm deep profile. The specific objectives were to: (1) develop an on-the-go integrated sensor consisted of a vertical sensor (disk coulter) for measuring soil mechanical resistance of soil surface layer (0–20 cm) and a horizontal penetrometer with prismatic tips for measuring HRI in subsurface depths (20 and 30 cm), (2) investigate whether there is any significant interaction between the two sensors while operating simultaneously, (3) evaluate the relationship between the CI and the disk coulter operating depth, and HRI and finally (4) investigate the behavior of sensor at two gravimetric water contents of 6 (low) and 13.5% (medium).

2. Materials and methods

2.1. Integrated sensor development

The on-the-go integrated sensor (Fig. 1) consisted of three parts: (1) a vertical sensor (an instrumented disk coulter) for measuring the penetrating depth of the coulter as indicator of the soil mechanical resistance at surface layer (0–20 cm), (2) a horizontal penetrometer (equipped with two prismatic tips) for measuring soil mechanical resistance in subsurface depths (20 and 30 cm) and (3) a data acquisition system.

The vertical sensor (Fig. 1) was an instrumented disk coulter which was 60 cm in diameter, 4.85 mm thick and sharpened on both sides, so the angle of the beveled edge was 17.2°. The disk was mounted on a hub connected through an arm to a frame. Two helical springs provided the disk with a downward force. The disk