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# A horizontal multiple-tip penetrometer for on-the-go soil mechanical resistance and acoustic failure mode detection

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ABSTRACT

Soil mechanical resistance can be used as an indicator of soil compaction. For on-the-go mapping of spatial variability in soil compaction, single and multiple-tip horizontal penetrometers have been developed and used to measure the soil mechanical resistance. However, it has been reported that the measured soil resistance in different soil layers depends not only on the degree of soil compactness but also on soil failure mode induced by the shank of the sensor. It was hypothesized that the differences in sound signals collected by microphones during penetration tests could be used to differentiate the failure modes. In this research, an acoustic multiple-tip horizontal penetrometer was developed, with three 30° prismatic tips attached horizontally to S-shape load cells and worked at depths of 10, 20 and 30 cm. The tips working at 10 and 30 cm depths were also fitted with microphones. The sensor was tested in a field with a clay loam soil. The sound signal was first de-noised using wavelet method, and then frequency spectrum and power spectral density of the signals were obtained by fast Fourier transform and Welsh's method, respectively. When the prismatic tips were operated below the critical depth of the sensor (tips at depths of 20 and 30 cm), there was a significant relationship between horizontal resistance index (HRI) and the cone index measured by a vertically-operated cone penetrometer; whereas for the shallower depth (10 cm) the relationship was not significant. The power of the sound recorded of the tip passing through the disturbed soil above the critical depth (10 cm) was much lower than when the tip was penetrating the undisturbed soil located below the critical depth (30 cm). The increase in power of the acoustic signal with depth was in line with the increase in the measured HRI. It can be concluded that the developed combined acoustic penetrometer can both detect soil failure mode and measure soil horizontal resistance.



## 1. Introduction

With advances in precision agriculture, spatial variation of soil compaction has been under focused investigation by many researchers (Hemmat and Adamchuk, 2008). It has been recognized that the recommended methods for direct measures of soil compaction are labour-demanding and cost-prohibiting for large-scale field mapping. Therefore, determination of indirect measures along with their geographical coordinates has become a more appealing alternative (Gaultney, 1989). In recent years, different prototypes of soil compaction sensor systems were developed for mapping certain predictors of soil compaction. Current soil compaction sensor systems are based on soil strength sensors (Hemmat and Adamchuk, 2008), fluid permeability sensors (Clement and Stombaugh, 2000), water content sensors (Alaoui and Helbling, 2006), or their combinations (Mouazen and Roman, 2006).

Soil strength, or mechanical resistance to failure, has been widely used to estimate the degree of soil compactness because it reflects soil resistance to root penetration (Taylor, 1971). On-the-go soil profile sensors can be used for measuring soil strength profiles throughout an agricultural field which typically involves either tip-based (ASABE, 2006; Chukwu and Bowers, 2005) or tine-based (Andrade-Sánchez et al., 2007) soil sensors. For on-the-go mapping of spatial variability in soil compaction, single (Alihamsyah et al., 1990; Hemmat et al., 2009) and multiple-tip (Hall and Raper, 2005; Chukwu and Bowers, 2005; Chung et al., 2006) horizontal penetrometers have been developed and used to measure the soil mechanical resistance. As this type of sensor moves through the soil, it registers resistance forces arising from cutting, breakage and displacement of soil, as well as the parasitic (frictional) forces that develop at an interface between the sensor surface and surrounding soil (Hemmat and Adamchuk, 2008).

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However, it has been reported that the measured soil resistance values in different soil layers depend on soil failure mode ahead of the sensor as well as the degree of soil packing and water content (Hemmat et al., 2009, 2012).

Hemmat et al. (2009) developed and field tested a single-tip horizontal penetrometer and reported the failure mode in front of it while penetrating soil at three different depths. The results showed that there was a significant relationship ($R^2 = 0.75$) between horizontal resistance index and the cone index as measured with a vertically-operated cone penetrometer when the sensing tip was operating below the critical depth—the depth at which the soil failure transitions from brittle to compressive occurs; however, the relationship was not significant as the sensing tip was moving through the disturbed soil above the critical depth. It was concluded that the correlation between measurements obtained with the vertically and horizontally operated penetrometers would be significant as long as the sensing tips of soil horizontal resistance sensors were operated below the critical depth and induced similar failure modes.

A major drawback of the single-tip horizontal penetrometer is that its measuring depth is constant; however, hardpan properties are not uniform across the field, but vary in depth and strength due to soil and crop factors, as well as farming and tillage practices (Raper et al., 2001). Due to the depth variability of the hardpan, researchers have been developing multi-tip horizontal penetrometers to measure soil strength in different layers simultaneously (Hall and Raper, 2005). Chukwu and Bowers (2005) developed and tested within a laboratory soil bin, a three-depth soil mechanical impedance sensor. It was reported that the sensor can measure differences in soil mechanical impedance with depth and location, and these impedances correlate well with corresponding cone penetrometer measurements. Chung et al. (2006) have further explored the idea of using multiple-tip horizontal penetrometer to estimate soil mechanical resistance at five depths. Field research (Chung et al., 2008) showed that soil strength measured by this sensor was a function of water content, bulk density, and texture. Best results were obtained when depth of operation was included in the regression model or when regression analysis was conducted within a single depth. Adamchuk et al. (2001) used an array of strain gauges attached to the backside of a vertical smooth blade to measure soil mechanical resistance at three depth intervals. An integrated sensor was developed and field tested by Hemmat et al. (2013) to measure the topsoil layer (0–20 cm) resistance using an instrumented disk coulter and the soil mechanical resistance at two discrete depths (20 and 30 cm) using a horizontal penetrometer with two prismatic tips. It was reported that the developed integrated sensor could be used to map the mechanical resistance of a soil profile to a depth of 30 cm.

A number of additional sensors that allow further soil characteristics to be determined can be placed within the penetrometer; including microphones for the detection of acoustic signals. This type of penetrometer is called an acoustic cone penetrometer and it has been used for geotechnical site investigation (Deutsch et al., 1989; Houlsby and Ruck, 1998) as well as agricultural applications (Liu et al., 1993; Grift et al., 2005; Moallemi-Oreh et al., 2010). As a cone penetrometer penetrates the soil, it makes an audible noise (Houlsby and Ruck, 1998). The microphone in the acoustic cone penetrometer detects acoustic emissions in the soils, due to particles being crushed, sheared or deformed as the tip penetrates the soil (Ruck, 1996). Acoustics has been applied to measure texture among four agricultural soil types (Liu et al., 1993) as well as soil type and properties in geotechnical applications (Ruck, 1996).

An alternative on-the-go approach to hardpan location measurement is based on measuring the sound level produced by a cone-shaped tip being drawn through the soil. An acoustic compaction layer detection system was developed by Grift et al. (2005) using a microphone-fitted cone mounted on a tine. To observe the acoustic effects of depth and soil density, constant-depth experiments at 15 and 30 cm depth were conducted under three densities, "no pass" (no hardpan), "single pass" (single compression hardpan), and "double pass" (double compression hardpan). Results showed that both soil depth and density had a detectable effect on the sound levels produced. In addition, the highest acoustic sensitivity to density was in the upper range of the frequency spectrum. Moallemi-Oreh et al. (2010) also developed an on-the-go acoustic soil compaction detection system using three equally-spaced microphone-fitted cone-shaped tips horizontally mounted on a vertical tine. With this arrangement, the soil compaction in three layers (5–15, 15–25 and 25–35 cm) was estimated based on power spectral density analysis of the sound created as the tine was pulled through the soil. Fast Fourier transform analysis showed a direct relationship between sound amplitude and compaction levels in the 5.5 to 7.5 kHz frequency range of the spectrum.

As stated above, the mechanical resistance sensed by the tips of a horizontally-operated penetrometer depends on both the degree of soil compactness as well as soil failure mode induced into the soil by the sensor shank. Therefore, for better interpretation of the results obtained by this type of sensor; it was hypothesized that by inserting microphones inside the tips of a multiple-tip horizontal penetrometer, besides measuring soil mechanical resistance, the differences in acoustic signals detected by microphones could be used to differentiate the failure modes. Therefore, the specific objectives of the research reported here were: (a) to develop a three prismatic tipped horizontal penetrometer for on-the-go measurement of soil mechanical resistance, (b) to detect soil failure mode by acoustic signals produced ahead of the prismatic tips and (c) to develop methods to characterize the acoustic signal.

## 2. Material and methods

### 2.1. Development of multiple-tip horizontal penetrometer

The multiple-tip horizontal penetrometer is composed of three groups of components: three prismatic sensing tips, a shank, and three load cells. The shank was designed to provide a method of inserting the force transducer and the soil strength sensing tips into the soil (Fig. 1a). The shank was constructed from SK45 steel, with a total shank length of 650 mm. The shank was designed to be pulled horizontally. The shank was designed so that the sensor would have a maximum effective measuring depth of 460 mm and a shank width of 22 mm to minimize the critical depth (the depth at which the soil failure transitions from brittle to compressive occurs) of the sensor and allow drilling oversized holes for passing through the rods of the tips. To limit the formation of a soil wedge in front of the advancing shank, the leading edge of the shank was bevelled to form a 30° prismatic wedge similar to the resistance sensing tips. This bevel was chosen to eliminate any soil from forming on the front of the shank as the shank is pulled through the soil, as per Hall and Raper (2005). The shank was designed to penetrate 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 bevelled to a 30° prismatic wedge. Three tips with 100 mm vertical spacing within a working depth of 300 mm were chosen to provide a 300 mm sensing profile and to minimize measurement interference from one tip to the next (Hemmat et al., 2012). Each prismatic tip was made of stainless steel and had an 18 mm × 18 mm base area with 30° apex angle. Each tip was connected to the load cell using a 16 mm rod, which passed through an oversized hole drilled in the shank. The length of the rod was such that the tip base was 40 mm ahead of