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Evaluating model-based relationship of cone index, soil water content and bulk density using dual-sensor penetrometer data

J. Lin [a], Y. Sun [b,*], P. Schulze Lammers [c]

[a] School of Technology, Beijing Forestry University, 100083 Beijing, China
[b] College of Information and Electrical Engineering, China Agricultural University, 100083 Beijing, China
[c] Department of agricultural engineering, University of Bonn, 53115 Bonn, Germany

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ABSTRACT

The relationship among cone index (*CI*), soil water content (θ) and bulk density (D_b) plays a critical role in assessing soil physical conditions. To predict D_b as functions of the measurements of *CI* and θ, a variety of semi-empirical *CI*-models have been established historically, however a study for validating these models has not been found. In this study four *CI*-models, one considered the penetration depth as variable but others did not, were evaluated under laboratory condition. The methodology was to use our own developed dual-sensor vertical penetrometer (DSVP) to simultaneously measure *CI* and volumetric soil water content (θ_v), and then to compare the bulk density (D_b) core-measured to that model-predicted by the DSVP data. Two types of soil samples (silt-loam and clay) were tested. Because a previous study speculated that penetration depth could confound the *CI* measured, two depth-dependent factors were incorporated into each *CI*-model for validating this speculation. Our study found that two of the four models tested fit the experimental data with acceptable R^2 (>0.70) and RMSE (<0.093 g cm^{-3}). In contrast, the experimental results confirmed that *CI* in Model-1 had a peak value adapting a wide range of θ. More ever, the results indicated that the DSVP combined with Model-1 or Model-2 can be used as a tool to predict D_b when *CI* and θ are simultaneously measured.

1. Introduction

Soil compaction is a major concern for agricultural field management because it can either positively or negatively affects plant growth and crop yield (Chen and Weil, 2011). Moderate compaction may speed up the rate of seed germination and reduce water loss, whereas excessive compaction results in higher soil strength and does not provide adequate pores and spaces for root's elongation (Tolon-Becerra et al., 2011; Modolo et al., 2011).

Soil compaction is commonly assessed through soil bulk density (D_b, g cm^{-3}), which can be determined by diverse methods. One method is cylinder core sampling. With known volume of the cylinder, D_b can be determined in laboratory. However, there are some shortcomings of this method. First, the sampling workload is too heavy to obtain a large quantity of core samples at different depths in the field. Second, it is time-consuming because the core samples should be oven-dried for 24 h at 105 °C for calculating D_b. Finally, the soil condition could be disturbed during the sampling process. Another available tool is gamma-ray tomography, but the potential risk of radiation exposure restricted its application (Hernanz et al., 2000; Borges and Pires, 2012). In contrast, penetrometer has been widely accepted as a practical instrument for assessing soil strength (Vaz et al., 2011). To make the penetration results comparable under different field conditions, the American Society of Agricultural and Biological Engineers ASABE Standards (S313.3, 2009a) recommended two types of penetrometers with a standard test procedure ASABE Standards EP542 (2009b). The standards also defined the cone index (*CI*, MPa) as penetration resistance (PR) divided by cone cross-sectional area.

Many previous studies noted that *CI* is not only strongly dependent on D_b, but also on soil water content and textural compositions (Busscher, 1990; Sojka et al., 2001; Vaz and Hopmans, 2001; Dexter et al., 2007; Santos et al., 2012; Quraishi and Mouazen, 2013a). For modeling the relationship among *CI*, D_b, soil water content (θ) and soil textures, Ayers and Perumpral (1982), Upadhyaya (1982) and Busscher (1990) presented different *CI*-models drawn from laboratory conditions. Thereafter, Hernanz et al. (2000) incorporated penetration depth as an independent variable into the Busscher model. For the soil samples tested, Ayers and Perumpral (1982) artificially made five ratios of Zircon sand to clay (0.1, 0.25, 0.5, 0.75 and 1.0 in sand percent) at three levels of D_b and eight levels of gravimetric soil water content (θ_g, g g^{-1}). The experiment of Upadhyaya (1982) was only concerned with

* Corresponding author. Tel.: +86 10 62737416/+86 10 82380725; fax: +86 10 62736741.
E-mail address: pal@cau.edu.cn (Y. Sun).

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silt-loam soil at multiple levels of θ_g. Busscher (1990) tested seven types of soils but detailed information of textural compositions was absent. Both Ayers and Perumpral (1982) and Upadhyaya (1982) used the ASABE standard cone penetrometer, whereas Busscher (1990) used a flat-tipped cone (diameter: 5 mm). These single-sensor penetrometers only measured the *CI* and were unable to account for the affecting factors on *CI*.

Over the past decades, with the intention for simultaneous measurements of penetration resistance (PR) and volumetric soil water content (θ_v), various soil water content sensors have been combined with the conventional penetrometers. One of these methods was Time Domain Reflectometry (TDR) sensor (Topp et al., 1996; Young et al., 2001; Vaz and Hopmans, 2001). An alternative method was to integrate near infrared spectroscopy sensors into the penetration rod (Newman and Hummel, 1999; Hummel et al., 2004; Quraishi and Mouazen, 2013b). Apart from these, capacitance sensors were embedded into a penetration rod (Singh et al., 1997) or a penetration cone (Sun et al., 2004). Although θ_v and *CI* have been simultaneously measured using the developed dual-sensor vertical penetrometers (DSVPs), to our knowledge no study has been reported for validating the developed *CI*-models by this advanced technique. Certainly, if a mathematical model was accepted as the best fit to the relationship of *CI*, θ and D_b, it would definitely benefit wide applications of the DSVPs. Thus, the aim of our study was to validate four of the existing *CI*-models using own innovative DSVP. For this, two soil types (silt-loam and clay soils) were tested under the laboratory condition.

2. Materials and methods

2.1. A general description of the concerned models

Model-1 presented by Ayers and Perumpral (1982) was

$$CI = \frac{A_1 D_b{}^{A_2}}{A_3 + (\theta_g - A_4)^2} \tag{1}$$

where D_b is bulk density in g cm^{-3}, *CI* is cone index in MPa, θ_g is gravimetric soil water content in g g^{-1}, A_1–A_4 are positive coefficients (dimensionless) and need to be determined with respect to specific soil types. For separating the effect of θ_g on *CI*, the following equation is used

$$\frac{\partial CI}{\partial \theta_g} = -B_1 D_b^{A_2} \frac{2(\theta_g - A_4)}{\left(A_3 + (\theta_g - A_4)^2\right)^2} \tag{2}$$

Furthermore, a maximum of *CI* in Eq. (1) can be found by

$$\left.\frac{\partial CI}{\partial \theta_g}\right|_{\theta_g = A_4} = 0 \tag{3}$$

since

$$\left.\frac{\partial^2 CI}{\partial \theta_g^2}\right| \theta_g = A_4 = -2\frac{A_1}{B_3^2} D_b^{A_2} < 0 \tag{4}$$

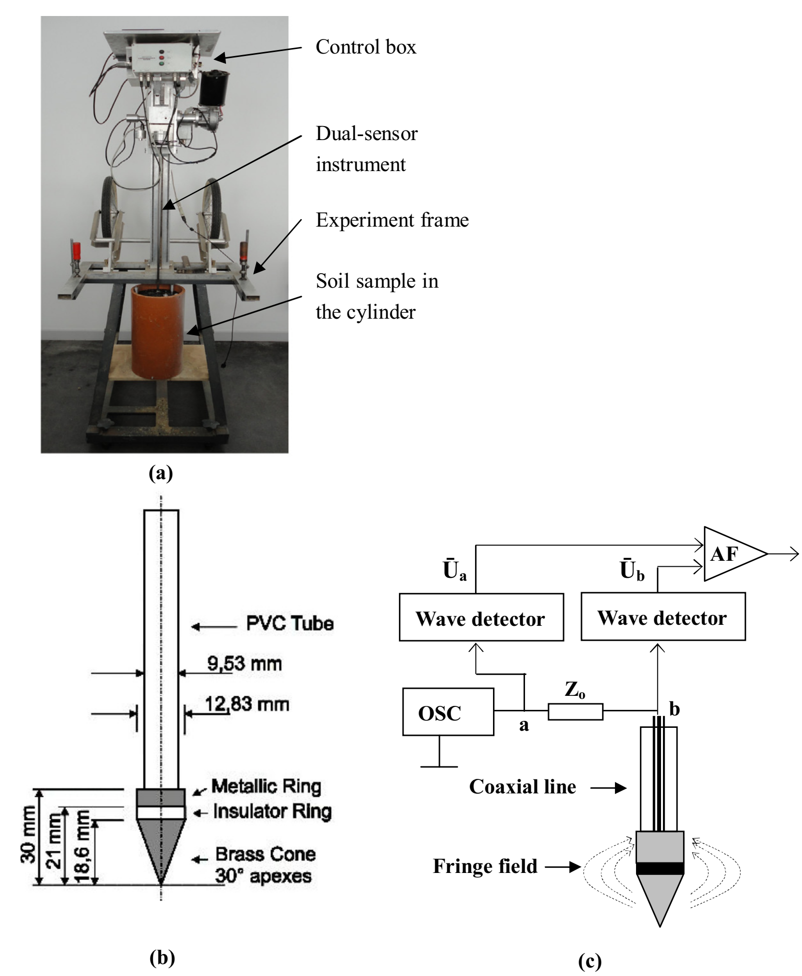

Fig. 1. The experimental system of the dual-sensing vertical penetrometer (a), electric layout of soil water content sensor (b) and the dimension of the combined cone, which met the ASABE standard (c).