Biosystems Engineering (2005) **90** (4), 381–396
doi:10.1016/j.biosystemseng.2004.12.004
PM—Power and Machinery

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A Tractor-mounted, Automated Soil Penetrometer–shearometer Unit for Mapping Soil Mechanical Properties

N.E. Boon; A. Yahya; A.F. Kheiralla; B.S. Wee; S.K. Gew

Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; e-mail of corresponding author: azmiy@eng.upm.edu.my

(Received 19 April 2004; accepted in revised form 2 December 2004; published online 10 February 2005)

A tractor-mounted, automated soil penetrometer–shearometer unit was designed and developed for the purpose of simultaneous *in situ* measurements of soil penetration resistance and shear stress. The automated soil penetrometer–shearometer unit utilises both commercial penetrometer and shearometer. The overall construction of the unit was made up of the main frame to support the moving carriage sub-assemblies, two moving carriage sub-assemblies to support penetrometer and shearometer, the gear driving mechanisms to support the traverse movements of the moving carriages, and the three-point hitch attachment to support the main frame and provide attachment to the tractor. The motion controls for the penetrometer–shearometer unit were performed by the programmable logic controller (PLC) unit and other external electronics and sensing devices. Two high-torque stepper motors were used to drive the penetrometer and shearometer moving carriages in the vertical axis direction while another one low-torque stepper motor was used to drive the rotating spindle of the shearometer. A personal computer data acquisition and differential global positioning system (DGPS) on-board tractor were used to assist in real-time measuring, displaying, and recording the tractor position, soil penetration resistance, and soil shear stress during the field sampling operation. Field test of the automated soil penetrometer–shearometer unit was conducted together with data collection on soil moisture content, terrain slope, and tractor–implement performance parameters. Spatial maps produced from the collected data showed considerable site-specific variation in the measured parameters over the field. Statistical analysis showed significant correlation between soil penetration resistance and shear stress and significant correlation between soil moisture content with penetration resistance and shear stress. Multiple regression equations were formulated using the stepwise analysis method to predict travel speed, implement draught and fuel consumption for mouldboard ploughing on Serdang sandy clay loam soil.

1. Introduction

Soil information is required in precision agriculture for managing and understanding crop growth and terrain trafficability. Soil penetration resistance and shear stress are among the soil parameters that affect crop production by limiting potential yield and affect machine mobility by limiting the potential traction. Regions of high mechanical resistance in the soil may result from natural soil features, heavy agricultural machinery traffic or the formation of tillage implement pans. Thus, soil quality must be determined and analysed in order to increase the crop productivity and machine trafficability. The collection and analysis of soil information in an efficient and effective manner in a site-specific scale at the field is therefore a scientific and technical challenge.

Soil penetration resistance is related to the pressure required to form a spherical cavity into the soil, large enough to accommodate the cone of the penetrometer, allowing for the friction resistance between the cones and its surrounding soil (Vaz *et al.*, 2001). *In situ* measurement of soil penetration resistance is carried out with special equipment known as a soil cone penetrometer in accordance with the procedure standardised in ASAE Standard S313.2 (ASAE, 2000a). Many researchers have attempted to simplify the usage of the penetrometer by various complicating design concepts (Raper *et al.*, 1999). Anderson *et al.* (1980), Wells *et al.* (1981), and Morrison and Bartek (1987) made hand-pushed type penetrometers with digital data recording systems. Hooks and Jansen (1986) and Sudduth *et al.* (1989) developed recording cone penetrometer with hydraulic cylinders. Riethmuller *et al.* (1983), Olsen (1988) and Larney *et al.* (1989) developed portable cone penetrometers driven by electrics motors. Wiltord *et al.* (1972), Soane (1973) and Smith and Dums (1978) developed a recording sol penetrometer that could generate cone resistance distributions maps. Clark *et al.* (1980) developed a digital recording cone resistance measuring system that could provide a constant penetration rate. Ohmiya *et al.* (1993) developed a computer-controlled cone resistance measuring system and visualisation software for generating two- and three-dimensional cone resistance distribution maps. However, manual operations, complicated measurement techniques, time consuming and limited sampling always become the measurement constraints for the application of the available penetrometers. The soil cone index is important in classifying terrain and the soil penetration resistance profile with the depth for quantifying the degree of soil compaction. It also contributes in providing a common system of characterising soil properties from which it may be possible to determine wheel numeric value or mobility number for predicting tractive performance (Wismer & Luth, 1974; Brixius, 1987; ASAE, 2000b).

Shear stress of soil is made up of the frictional resistance met by soil particles when they are forced to slide over one another or to move out of interlocking positions, the extent to which stresses or forces are absorbed by solid–solid contact among the particles, cohesive forces related to chemical bonding of clay minerals, and surface tension forces within the moisture films (Morgan, 1986). *In situ* measurement of soil shear stress is carried out with special equipment known as soil shearometer. Measurements were conducted by pushing the shearometer vane into soil surface until the blades were covered and a clockwise rotation rate was then applied to ensure that failure developed within 5–10 s (Zimbone *et al.*, 1996). Many *in situ* measurement techniques of torsional and penetration resistance have been used to measure the soil surface shear (Rauws & Govers, 1988). However, the employed measurement techniques were complicated, time consuming and difficult to apply for large-scale measurement. Furthermore, relationships between the various measurement techniques for shear resistance were often not available and the data collected by various employed methods were not easy to compare (Zimbone *et al.*, 1996). The shear stress of soil is important in quantifying the potential soil shear failures cause by tires and tracks of agricultural machinery. Bekker (1969) and Wong (2001) developed empirical traction prediction equations for tires and tracks based on soil shear stress.

This paper describes the design, development, and testing of an automated soil penetrometer–shearometer unit for measuring soil penetration resistance and shear stress. The developed unit is a part of the novel precision instrumentation system in the Massey Ferguson 3060 tractor to be used in the generation of a comprehensive database on the power and energy demand mapping of agricultural field operations in Malaysia (Yahya *et al.*, 2002).

2. Materials and methods

2.1. *Mechanical structure*

The overall construction of the complete soil penetrometer–shearometer unit was made up of the following four main sub-assemblies; the main frame to support the moving carriage sub-assemblies, two moving carriage sub-assemblies to support penetrometer and shearometer, the gear-type driving mechanisms to support the traverse movements of the moving carriages, and the three-point hitch attachment to support the main frame and provide attachment to the tractor. The complete unit has overall dimensions of 1025 mm in length, 360 mm in width and 1265 mm in height. *Figure 1* shows the design construction of the automated soil penetrometer–shearometer unit and *Fig. 2* shows the complete system that is mounted on the tractor.

A penetrologger (06.15, Eijkelkamp Agrisearch Equipment, Netherlands) and vane test apparatus (I012, RMU Test Instrument, Italy) were used as the main components of the soil penetrometer–shearometer unit. The penetrometer and shearometer unit offers *in situ* measurement as well as recording of soil penetration resistance and shear stress. Measurement on the penetrometer could be made up to 10 MPa range at an accuracy of 0.01 MPa resolution while the shearometer was able to give a measurement range from 50 to 60 Nm at an accuracy of 0.1 Nm resolution. The penetrometer and shearometer units were housed in a main frame, which was constructed from mild steel hollow rectangle sections. Two sets of ball screws were vertically located inside the main-frame sub-assembly. The 20 mm diameter ball screw set with flange bearings at their ends were used to support the penetrometer carriage traverse motion. The 25 mm diameter ball screw set with flange