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Development of a Hydraulic-driven Soil Penetrometer for Measuring Soil Compaction in Field Conditions

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Abstract: Soil compaction is an important physical limiting factor for root emergence and the growth of plants. Therefore it is essential to control soil compaction, which is normally caused by heavy traffic in fields during the growing season. Soil compaction in fields is usually measured by using standard soil cone penetrometers, which can be of several different types according to their design. Most of the time, especially in heavy soil conditions, measuring soil compaction with a standard hand Penetrometer produces measurement errors if the cone of the penetrometer cannot be pushed into the soil at a standard rate. Obtaining data with hand penetrometers is also difficult and takes a long time and effort. For this reason, a three-point hitch-mounted and hydraulic-driven soil cone penetrometer has been designed in order to reduce time and effort and to reduce possible measurement errors in the sampling of soil compaction data for research purposes. The hydraulic penetrometer is mounted on the three-point hitch and a hydraulic piston pushes the standard penetrometer cone into the soil at a constant speed. Forces acting on the cone base are recorded with a computer-based 16-bit data acquisition system composed of a load cell, a portable computer, signal amplification and necessary control software for the sampling. As a conclusion, the designed and constructed three-point hitch-mounted hydraulic-driven standard soil cone penetrometer provides with quick and very accurate measurements about soil compaction in clay soil in heavy conditions.

Key words: Penetrometer, cone index, soil compaction, heavy traffic

INTRODUCTION

Soil compaction is an important physical limiting factor for plant growth and root emergence (Hummel *et al*., 2004; Hall *et al*., 2005). In general, compaction of 80 kPa or more results in the blocking of root emergence of plants (Bowen and Goble, 1967). Several factors, such as heavy traffic in the field, seedbed preparation in unsuitable soil conditions and overburdening of the field for a better yield of unique crops by agricultural operations, create a high level of soil compaction, causing unwanted soil conditions for the yield. Starting from the seedbed preparation for a particular plant, fertilizing and chemical application, as well as harvesting, require the use of heavy farm machines that mostly cause high compaction in the top layer of the soil in a short time. On the other hand, the heavy and frequent use of farm machines compacts the subsoil in the long term regardless of the soil type. It has been reported that almost 90% of the field area is pressurized by the tractor tyres at seedbed preparation, 35% at harvesting and finally, 60% at baling respectively (Munsuz, 1985). As a result of heavy traffic in the field, the soil particles are reoriented and the porosity of the soil is reduced. In addition to this, the subsoil becomes a compacted soil layer which prevents soil water infiltration through the depth and that results in up to a 30% decrease in yield (Al-Adawi and Reeder, 1996). Therefore, some researchers are interested in focusing on subsoil compaction and methods of tillage to control hardpan (Al-Adawi and Reeder, 1996; Birkas *et al*., 1998; Kavalaris and Gemtos, 1998).

Soil compaction is commonly measured by cone index using a soil cone penetrometer. A simple penetrometer is a penetration rod having a conical tip with a force sensor, which may be a strain-gauge or piezoelectric load cell (Sun *et al*., 2004). The Cone Index (CI) is a technical term that is defined as the penetration force divided by a standard cone base area during the penetration of the soil with a standard soil cone penetrometer at a constant penetration rate (Anonymous, 1983; Sun *et al*., 2007). The standard penetrometer cone has a 30° cone tip angle and a one-inch base diameter. The standard penetration rate is also reported as 30 mm^{-1}.

Soil compaction measurements usually take place in field conditions for agricultural research purposes.

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Besides soil compaction, many factors, such as soil water content, soil texture and penetration velocity, may also have impact on CI during measurement (Perumperal, 1987; Topp *et al*., 2003). Because of their physical limiting characteristics for the plants, some research is concentrated on tractor tyres and soil interaction (Özgöz and Okursoy, 2002). There are some mathematical relationships between soil penetration resistance and soil bulk density as well as the soil moisture content. Although some of them have an exponential relationship between cone index, soil moisture content and soil bulk density, most of them have a nonlinear relation between these parameters over a certain range (Koolen and Vaandrager, 1984; Froehlich and Ellwein, 1990; Okursoy, 1997). In literature, most researchers have also reported that the accurate measurement of soil compaction *in situ* yields is necessary. One of them for the CI measurements, a multi-penetrometer array was developed that could be mounted with its outer frame to the front coupling device of a tractor (Domsch *et al*., 2006). They have also reported that reducing measurement errors depends upon several parameters such as the penetrometer type and its driving units (Raghavan *et al*., 1977; Morrison and Bartek, 1987; Raper *et al*., 1999).

Measurement of a large amount of soil compaction using a hand penetrometer with high accuracy also requires more time and extreme effort in field conditions. The objective of this study is, to design and construct an accurate three-point hitch-mounted hydraulic-driven standard soil cone penetrometer for measuring CI in order to reduce the time and effort.

MATERIALS AND METHODS

The designed penetrometer can be examined in two main parts, namely the mechanical components of the device and the electronic data control card and acquisition systems including force and soil depth sensor. The mechanical components of the penetrometer include a frame, three-point hitch and a hydraulic cylinder and its components. The mechanical units of the system were constructed in a research workshop. The three-point hitch located on the penetrometer frame has standard dimensions and the frame was made by standard beams.

As the power unit, the hydraulic cylinder is powered by timing gears and couplings, which are located in a tractor hydraulic pump. The oil flow of the pump depends on the motor rotation of 1400 rpm, producing 12-18 L min^{-1} oil flow through the penetrometer hydraulic cylinder. In Fig. 1, the constructed hydraulic soil penetrometer is presented. The hydraulic cylinder provides the penetrometer tip constant and standard penetration rate for the penetration. For a 30 mm sec^{-1} penetration rate, oil flow for the cylinder is 2.26 L min^{-1}

Fig. 1: Three-point hitch mounted hydraulic-driven soil penetrometer

and the oil pressure for the cylinder is 30.8 bar, respectively. In addition to this, the penetrometer cone penetrates the soil to a maximum of 40 cm, therefore a 40 cm stroked hydraulic piston was used. The oil flow is controlled by a two-way fluid flow check valve which has a maximum 210 bar internal oil pressure capacity and maximum 1.54 L min^{-1} flow rate capacity. The flow control valve on the hydraulic system is left in the open position during the penetration process and is controlled manually by a control switch on the tractor. Because the standard penetration rate of the penetrometer is 30 mm per sec^{-1} and the maximum penetration depth is 40 cm, taking data from a location takes 13.3 sec^{-1}, which is a very short time. In addition to this, the hydraulic system includes a spring-controlled pressure safety valve that provides the system with a safe operation by adjusting oil pressure at given adjustment intervals. If the load exerted by the hydraulic piston exceeds 500 kg, the spring-controlled valve opens the gate to move pressurized oil back to the system tank.

The soil depth sensor is made by rotational encoder, which is actually a roller pulley with a belt drive. When the hydraulic piston pushes the penetrometer rod, the cone starts to penetrate the soil. Similarly, when the penetration starts, an elastic belt turns the small pulley, which generates an electronic signal by the rotation. The generated analogue signal is then amplified and converted into digital forms by the data acquisition control box, which was also designed and placed in a tractor cabinet with the necessary parts. The data from the control box is converted into digital data by means of an 8-bit ADCO831 integrated chip, having a 5V measurement excitation and 1.4 mV per degree rotation. The sensor pulley is calibrated at 10 rotations corresponding to the maximum penetration depth, which is 40 cm. This gives a minimum of 0.15 cm per bit as the measurement sensitivity of the depth sensor (Tekin and Okursoy, 2001).

Soil compaction measurements also require the measurement of penetration forces acting on the penetrometer cone during the penetration process. The force sensor is an S-type force transducer that is placed and covered between piston and penetrometer rod. The load cell of the force transducer is actually a bridge circuit which needs 5 V to excite and reach an electronic balance. When a penetration force acts on the cone, the electronic balance of the bridge circuit changes and the circuit produces output signals that are amplified and converted into digital forms for the calibration. The digital conversion of the output signals is performed by ADC7715 and the reference voltage of the circuit is produced by AD780 for the comparison. Therefore, the full scale measurement interval of the circuit is 20 mV, which corresponds to a 500 kg load with a measurement sensitivity of 0.007 kg. Calibration results of the force sensor shows that there exists an exact linearity between the output of the force sensor and the exerted force ranging from o-500 kg. Penetometer tests were conducted in a clay soil in heavy conditions at the Uludag University Research Farm, in Bursa (29:04 E; 40:11 N) in October. The average soil moisture content in a dry base was also obtained as 28% by taking soil samples at those locations.

RESULTS AND DISCUSSION

The results of measurement data from four locations in the field produce expected cone index-depth graphs which are given in Fig. 2. The graphs of cone index versus depth are prepared from the raw data and at 2 cm depth intervals. From Fig. 2, at the first location, the average soil compaction is measured approximately as 203 kPa, which was a constant until the penetrometer cone reached a soil depth of 4 cm. After that, a rapid increase was observed in cone index values such as 1025 kPa at a depth of 12 cm. This kind of measured data can be observed in clay soil. When the locations are changed, different cone index values come out, but the shape of the soil compaction curves looks the same. It was also found that the cone

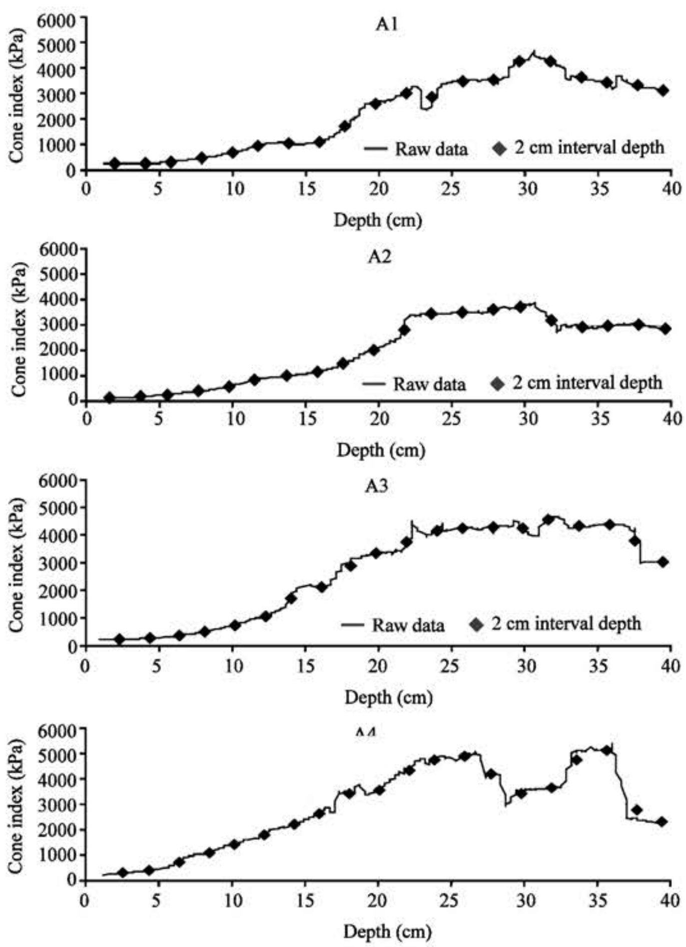

Fig. 2: Measured cone index with respect to soil depth

index values at the soil surface were very low as expected at all locations. This is explained by the fact that the penetrometer cone started to sense the soil compaction just after the cone had started to penetrate the soil. In general, the same conclusion can be drawn for all the measured data points, although there are small differences in the shape of the cone index curves for some locations.

CONCLUSIONS

As a conclusion, In this research, a three-point hitch-mounted hydraulic-driven soil cone penetrometer was designed and constructed in order to reduce the time and effort. The designed and constructed three-point hitch-mounted hydraulic-driven soil cone penetrometer provides us with quick and very accurate measurements about soil compaction in clay soil in heavy conditions. Taking data from a location takes 13.3 sec at the maximum penetration depth 40 cm, which is a very short time. Because the control computer for part of the data acquisition system is placed in a tractor cabinet, obtaining soil compaction data in the field, even in unsuitable soil and weather conditions, is easily performed. It can also be concluded that the device is promising for future research projects related to determining soil compaction maps during the growing season for a particular plant in certain soil conditions. More than one penetrometer rod can be used for measuring soil compaction for further research.

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