Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2019) 43: 151-163
© TÜBİTAK
doi:10.3906/tar-1803-64

Design and development of a front mounted on-the-go soil strength profile sensor

Arif Behiç TEKİN*, Harun YALÇIN

Department of Agricultural Engineering and Technology, Faculty of Agriculture, Ege University, İzmir, Turkey

Received: 13.03.2018 • **Accepted/Published Online:** 03.12.2018 • **Final Version:** 01.04.2019

Abstract: Soil compaction is a great problem since it affects crop growth and yield. The causes of soil compaction are the management practices in agricultural production. A common practice is to implement subsoiling at a few centimeters below the hardpan. Management practices, field traffic, and variations of the soil's physical and chemical properties throughout the field cause variations in the soil compaction degree and depth. Subsoiling at certain depths can cause excessive energy consumption at a high cost. Therefore, agricultural tillage equipment could be improved by varying the tillage depth. Soil strength is the main indicator that depends on several soil properties such as bulk density, moisture, and organic soil texture content for determining the compaction level. The goal of this study was to develop an on-the-go sensor. It measured soil strength at multiple depths in order to determine the depth of the compacted soil layers. The mechanical frame of the sensor (body) was designed using Solidworks 3D CAD Design Software. Depth measurements were based on the Programmable Logic Controller (PLC) system. The data-gathering algorithm was developed with Phoenix Contact PC WORX software. It recorded the data flowing from the load cells, calculated the depth of the hardpan, and altered the depth of the chisel. In order to calibrate the load cell and compensate for differences among the load cells, static tests were conducted in a laboratory. The consistency of the sensing tips in terms of the input load – output load harmony was in linear format with higher R^2 values ranging between 0.98 and 0.99. Consequently, the on-the-go soil sensor was developed for variable depth subsoiling. Dynamic tests revealed that the sensor was capable of monitoring the soil strength through the profile in order to determine the compaction level and hardpan depth. Moreover, the sensor was capable of adopting itself to crop varieties that have different critical compaction levels for root penetration.

Key words: On-the-go sensor, soil compaction, sustainable agriculture

1. Introduction

Over the last few decades, the philosophy known as smart agriculture has aimed at the management of heterogeneity in agricultural production to improve farm profitability and productivity, and to decrease negative pressure on the environment, as well as to comply with agronomic requirements and related technologies, which have been considered to be a new revolution in the agricultural domain. Due to the recent application developments in agricultural technology, which are available on the Internet, Tekin (2016) called this approach Agriculture 4.0.

Agriculture 4.0 assists farmers by creating detailed records of the entire farm operation along with providing information on sensors, vehicles, etc. It is an information and communication technologies application that allows data to be automatically generated and recorded, as well as allowing for the coordination of vehicles and hardware in order to manage the heterogeneity. Moreover, it assists farm managers with the optimization of agricultural production by reducing inputs and increasing the profit. It also allows farmers to certify that the entire production process is correct in order to declare to their customers that the products were produced in a sustainable manner. The implementation of smart agriculture or Agriculture 4.0 applies inputs at the right volume, at the right time, at the right location, and with the right method.

During this new revolution, the first attempts were focused on soil and yield mapping to quantify and understand the variability. Then experts began to study fertility based on the reports from previous researchers. Soil mapping operations were conducted by collecting soil samples from predefined locations using a map-based approach and the soil samples were then sent to a laboratory for analyses. All of this caused a decrease in the profit for the farmer. Latter activities dealt with sensor-based applications due to several constraints such as data collection cost and rising labor demands from the map-based applications. Therefore, experts have been focused on the portable sensing of the soil structure. Based on the data measured from these sensors, the next step was the implementation of variable-rate technology by altering the input volume.

* Correspondence: behic.tekin@ege.edu.tr

1.1. Soil compaction and hard-pan

Soil compaction is one of the great concerns in crop production and environmental pollution (Way et al., 2007). Soil compaction often restricts root development and growth due to increased bulk density and/or strength of the soil, reduces the biological activity of plant roots and organisms in the soil due to reduced aeration, and limits water infiltration, resulting in an increased potential for runoff and erosion. Moreover, soil compaction problems reduce crop yields by 25%, 30%, and even 40% (Wells et al., 2003).

Field traffic and farming operations are caused by an increase in bulk density. The weight of agricultural vehicles, depending on the interaction between tire and inflation pressure, significantly affects the soil bulk density (Way et al., 2007). It can be caused either by soil conditions or by natural processes.

Conventional soil compaction management methods are based on the use of triennial/quadrennial deep tillage, usually at a uniform depth of 20 to 40 cm; these require excessive fuel consumption and are time-consuming (Çakır et al., 2007). Intensive tillage leads to an increase in operation costs and deteriorates the soil structure over the years. There are several handicaps of this approach to the remediation of soil compaction. A few facts that growers may not be aware of include whether or not the breaking up of soil compaction is needed, where in a field it is required, and at which depth. Moreover, the depth and thickness of the compacted levels vary throughout the field. Studies have reported that the depth of compacted layers varied greatly from parcel to parcel and within each parcel. Subsoiling operations at fixed depths may be too shallow or too deep and can be expensive (Khalilian et al., 2002). Raper et al. (2003) reported that the tillage power requirements could be decreased by 27% with variable depth tillage compared to uniform-depth tillage.

To cope with the drawbacks expressed above, variable depth subsoiling is an optimized solution. Subsoiling at variable depths improves the local soil conditions by varying the tillage depth based on what is necessary for maximum plant growth. It could lead to considerable energy and fuel savings and minimize gas emissions created by tractors. Fulton et al. (1996) determined that the fuel savings could be increased by up to 50% by using variable depth tillage as compared to fixed depth tillage over the entire field. Raper (1999) declared that the high fuel costs could be lowered by as much as 34% with variable depth subsoiling compared to a uniform-depth.

The first step in soil compaction remediation is to measure the soil strength and depth by using tools, devices, or sensors. Measurement devices mostly use vertical or horizontal measurement methods and consist of a force transducer, which is a load cell (Sun et al., 2004) used to measure the soil strength while mowing in the soil (Smith, 2007). The standard scientific method in evaluation of soil compaction strength is represented by the cone index (CI), which is defined as the force per unit of the basal area required to force a standard cone tip through the soil profile (Fountas et al., 2013).

The development stage brought about electronic instruments that were able to monitor the penetration resistance via strain gauges, and penetrating depth through the use of distance measurement sensors (Fountas et al., 2013). An embedded data logger on the penetrometer recorded the measurements. Simultaneously, the American Society of Agricultural and Biological Engineers (ASABE) developed standards for the penetrometer in order to have comparable records of the measurements taken by users (ASABE, 2010). The latest devices developed to measure soil strength consist of a GPS module to record measurement locations that allow users to create a soil compaction map as shown in Figure 1 (Hemmat and Adamchuk, 2008).

This compaction map may be used for variable depth subsoiling operations. On the other hand, many factors, such as soil water content, soil texture, and the penetration velocity of the measurement tip, could affect the measurement sensitivity (Perumperal, 1987; Topp et al., 2003). Normally, the velocity that reduces the measurement sensitivity of hand-held devices might not remain consistent. In order to overcome this problem, experts have developed vehicle-mounted devices for farm equipment such as all-terrain vehicles, pick-up trucks, and tractors (Alimardani, 2005; Tekin et al., 2008; Topakci et al., 2010; Fountas et al., 2013; Kumar et al., 2015). In order to improve the speed of measurements in the field, researchers developed multiprobe soil cone penetrometers (Raper et al, 1999; Fountas et al., 2013)

It is clear that the recommended methods for direct measurements of soil compaction require labor-intensive demands and high costs for large-scale field mapping (Hemmat and Adamchuk, 2008). These handicaps increase the demand for indirect measurements along with or without their geographical coordinates, and are more appealing as an alternative (Gaultney, 1989). Hemmat and Adamchuk (2008) reported that simultaneous mappings of soil strength at multiple depths would significantly improve the soil compaction information.

Variable depth tillage implementation is based on either a map or a real-time sensor technology. The map-based approach requires a two-step operation; the first step is to map the depth of the compacted layer, and the second step is to implement subsoiling at a variable depth.

In contrast, the sensor-based implementation is a single step operation that results in less traffic and fuel consumption, and saves time. Moreover, it provides a uniquely assembled robust system.

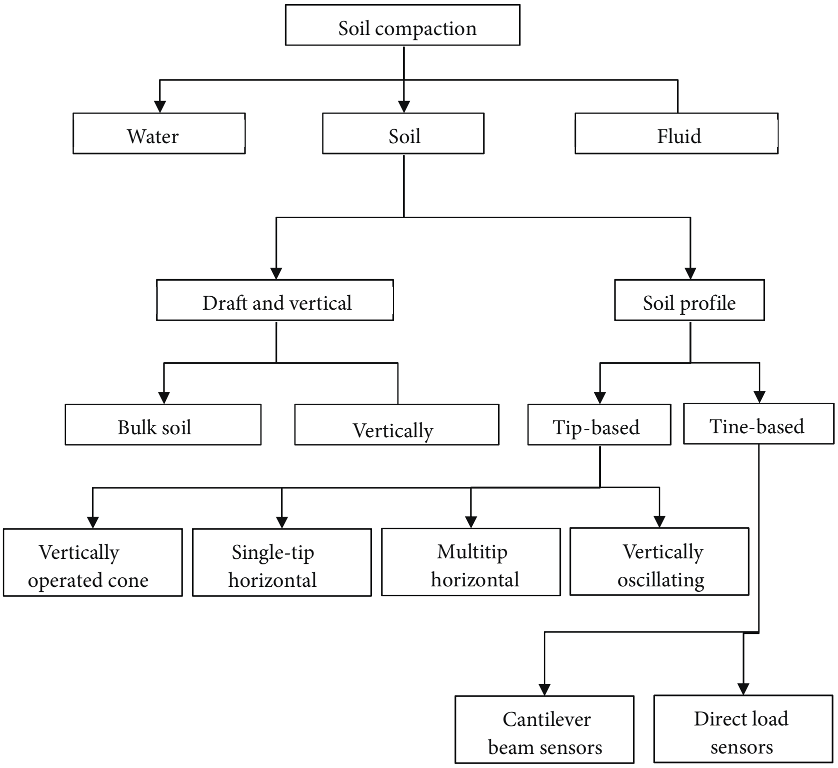

Figure 1. Classification of soil compaction sensor systems.

Several researchers (Chung et al., 2003, 2004a, 2004b, 2005, 2006; Chung and Sudduth, 2003a, 2003b, 2006; Chukwu and Bowers, 2005; Topakci et al., 2010) focused on this approach and developed prototypes. Chung et al. (2003) reported that although prototype sensors have been capable of providing on-the-go soil compaction data, they are all still in the development stages.

The objective of this study was to develop a sensing part of this uniquely assembled system for the remediation of the compacted layers that limit plant growth. The concept of the prototype system was based on the predetermined depth of the compacted layer via horizontal soil strength measurements before a tractor pass occurred.

2. Materials and methods

The advantage of the horizontal sensor design, a tine-based concept, was that it allowed for on-the-go measurements of the soil's mechanical strength at various depths. The force-sensing tips were located in the front of the narrow soil-cutting blade and interfaced with load cells that were located inside the blade. Specially designed frames held the blade. The frame moved on four wheels and was linked to a hitch, which was positioned in the front of the tractor (Figure 2). The linkage between the tractor and the sensing blade was a parallelogram mechanism, which allowed the sensor to match the soil surface variations. The design process included issues such as soil strength sensing, sensor design, load cell selection, data acquisition, and system calibration.

Figure 2. The sensor with a tractor attachment system.

2.1. Tine and sensing tips

Figure 3 and Figure 4 show the assembled structure of the soil strength-sensing tine as viewed: the frame comprised the tine, load cells, and prismatic tips for sensing of the soil strength. Chung and Sudduth (2004) studied CI profiles and reported the maximum sensing depth

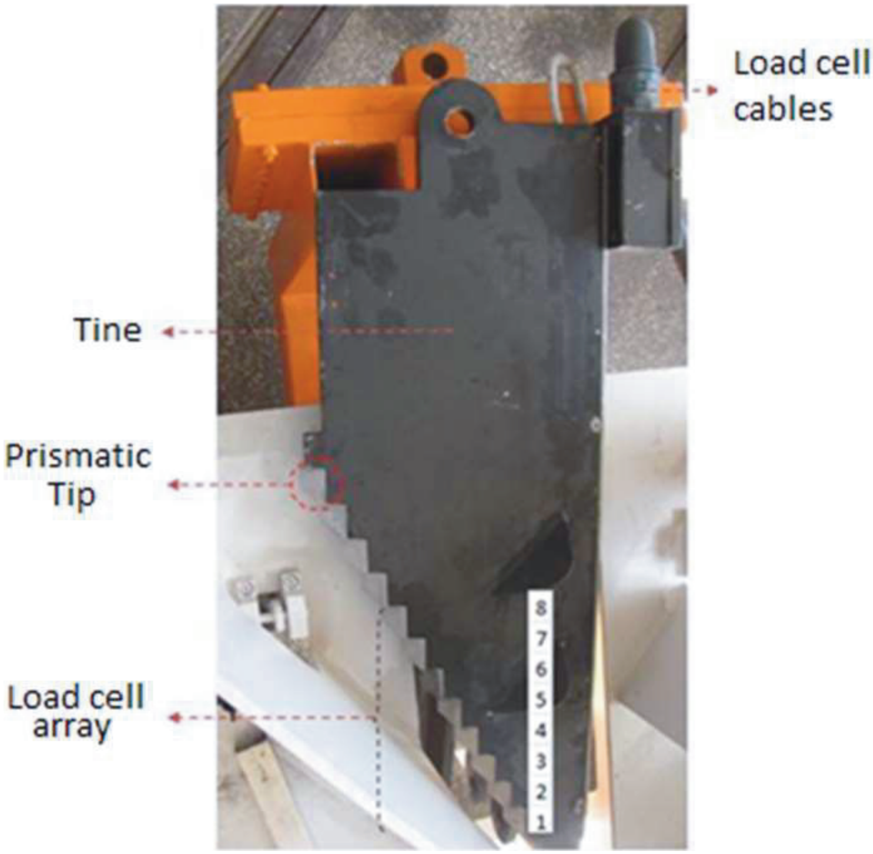

Figure 3. Sensor blade: **s**ensor tine, sensing tip, load cells, and cables.

and expected maximum soil strength as 0.50 m and 10 MPa, respectively. Design parameters, such as materials and dimensions, were determined based on these data. Two limiting factors of the blade's design were the tine thickness and load cell dimension. Although the tine thickness had to be as narrow as it was, its overall thickness was determined by the minimum size of the load cells in the market meeting the force requirement. The tine and prismatic tips (Figure 5) were made of stainless steel (AISI No. 17-4PH). The tine had metal wings on both sides so that it could keep itself at the indicated depth setting. Before manufacturing, the tine deformation was analyzed in SolidWorks Simulation Xpress (SolidWorks 2011, Dassault Systèmes SOLIDWORKS Corp., France) in order to check the reliability of the mechanical body in the chosen dimensions (Figure 6). Moreover, based on previous research (Chung and Sudduth, 2004) in order to follow the variability in soil strength, a tractor speed of 2 m s^{-1} and a sampling frequency of 4 Hz were selected. A prismatic tip with a 60° apex angle was selected as the sensing tool (Figure 5). The lower edge of the tip contained another designed parameter in order to eliminate the side effects of the soil disturbance created by the lower part of each tip, which affected force sensing.

2.2. Load cell selection

The load cell was selected by taking into account previous research results (Chung and Sudduth, 2004), the size and design of the sensor's tip, and the expected maximum values of soil resistance (Figure 6). The maximum expected force was calculated as 10 MPa × 1200 mm^2 (the projected area of the sensing tip) = 12 kN. The prismatic sensor's tip had two edges with different shapes. While one edge of the tip had a prismatic shape, the other edge had a circular shape, which interfaced with the load cell that was selected for design. The dimensions of the load cell determined the dimensions of the circular edge. Hardpan thickness featured the dimensions of the prismatic edge due to measurement precision. Goodson et al. (2000) reported that the thickness of the compacted layer could vary from 5 mm to 12.7 mm. Therefore, in order to monitor the depth and thickness of the compacted soil layer, the height of each tip was determined to be 40 mm and soil resistance was measured in 40-mm increments. After a survey of available commercial products, a miniaturized circular load cell with a diameter of 12.7 mm (model LCM307-10KN, Omega, USA) was selected (Figure 7). The safe overload was 150% of the sensor's capacity.

The sensor had a full bridge circuit of strain gauges with a temperature compensation range of 16 °C to 71

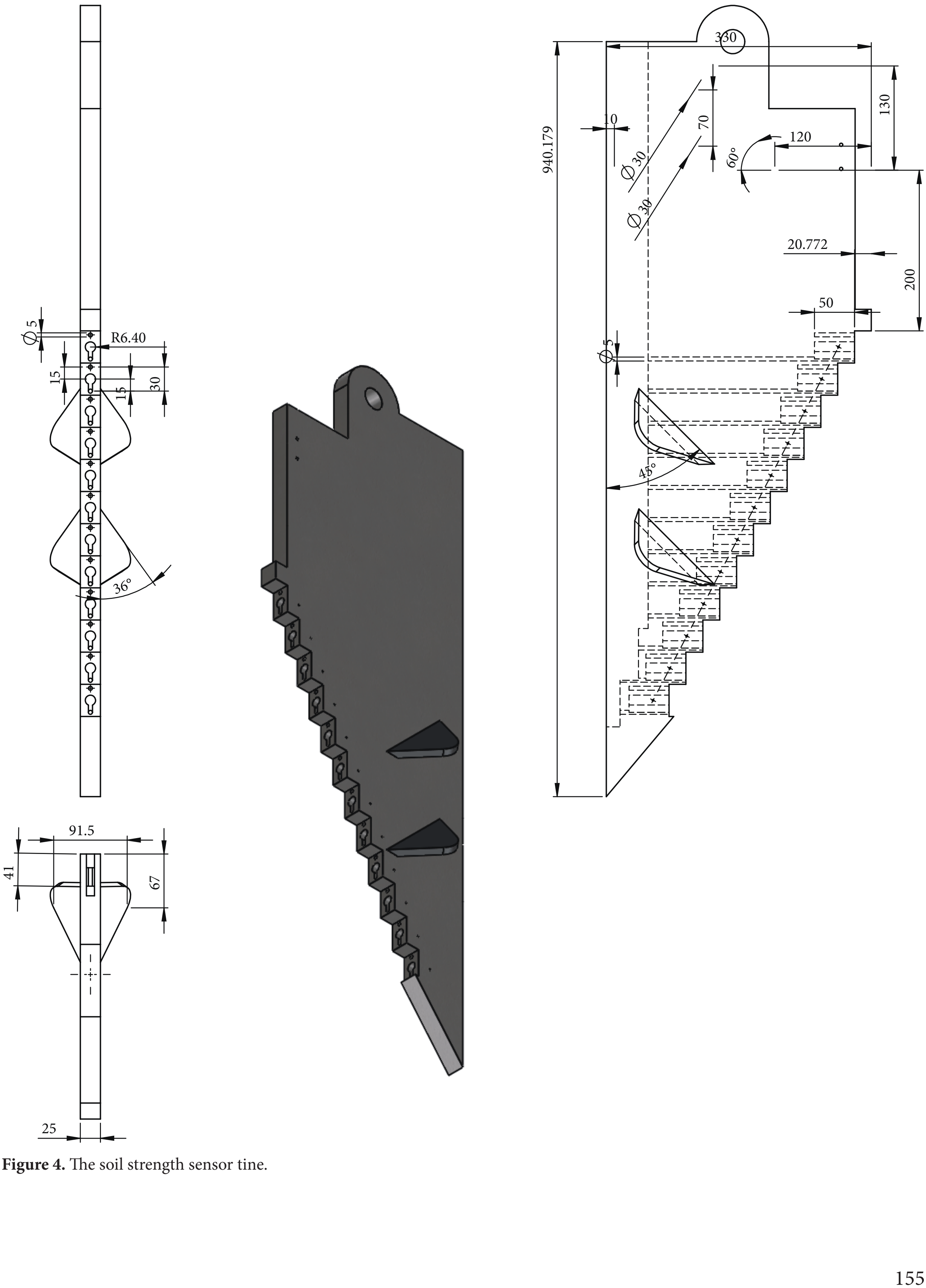

Figure 4. The soil strength sensor tine.

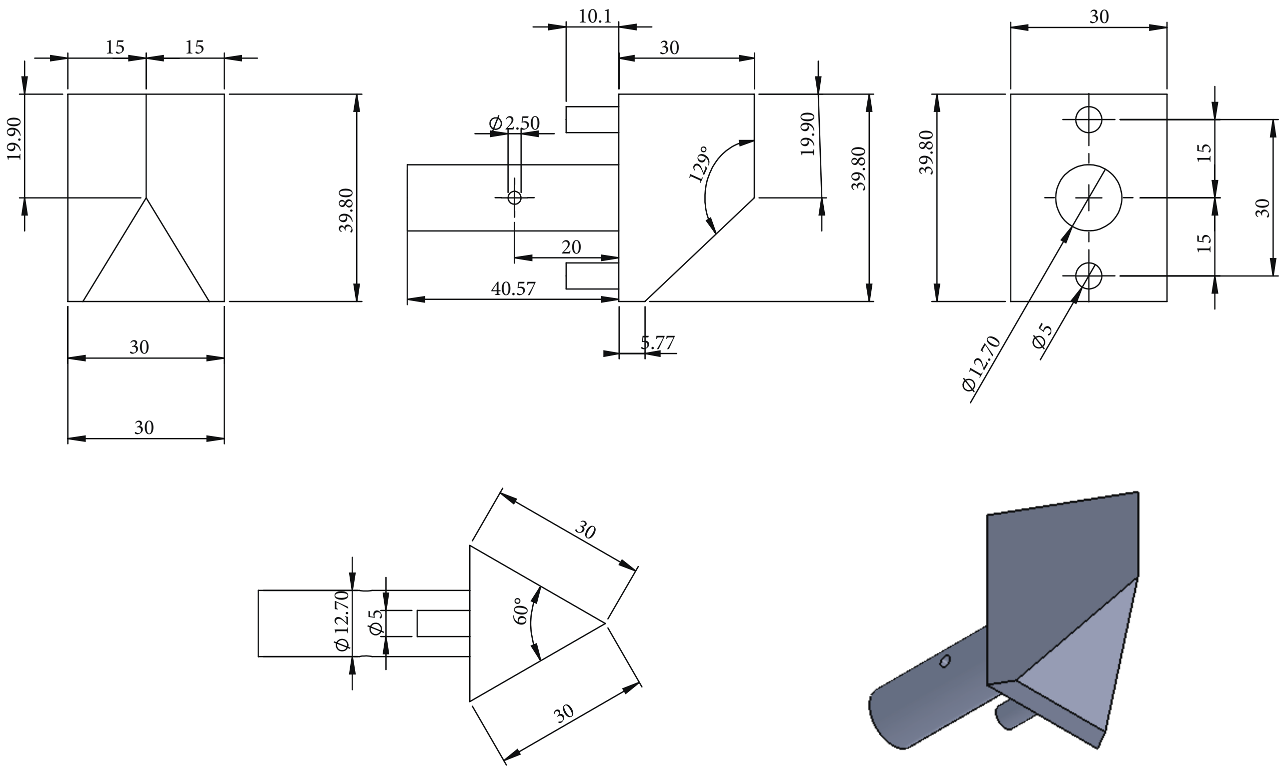

Figure 5. The prismatic tip used as the sensing tool.

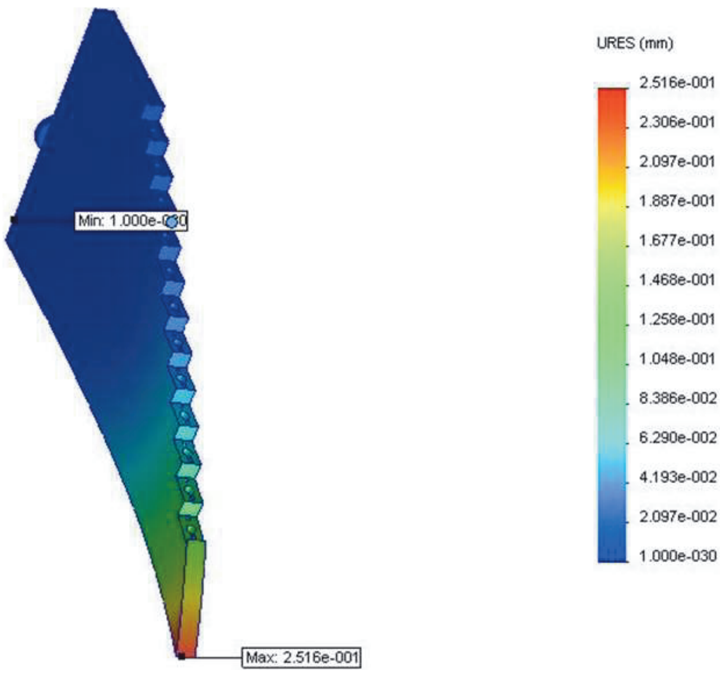

Figure 6. Stress analyses of the sensor tine.

°C while its operating temperature range was –54 to 121 °C. The load capacity and accuracy (including linearity, hysteresis, and repeatability) of the load cell was 0 to 10 kN and 0.75% of full scale, respectively. Excitation voltage was 5 Vdc and output was 1.5 mV/V. Excitation input of 5 V was used, resulting in a 7.5-mV signal at 10 kN.

In order to calculate the soil penetration resistance, the software used an equation to convert the output signal

Figure 7. Load cell for force measurement.

The chassis held a hydraulic cylinder system to address the downward insertion of the sensor prior to the measurements and to keep the operating depth at a set value. The frame had supporting wheels, which assisted the hydraulic cylinder. By applying this mechanism in heavy residue or soft soil conditions, the continuous measurement of sensing depth could be kept constant. A shear bolt mechanism was designed to protect the load cells and tine from excessive loads. In order to design this mechanism with an assumed force on the tine, a linearly increased stress was applied with soil depth from 0 MPa at the soil surface to 10 MPa at the deeper end of the tine. These load settings were chosen because 10 MPa was the expected maximum soil strength and 0 MPa was a reasonable boundary condition at the soil surface.

Laboratory calibration tests were conducted on the sensor under static conditions. After manufacturing of the tine, the sensor's load cells were statically calibrated by applying loads in the range of 0–160 kg using a scaled weight and the output loads (derived from the output voltage) were recorded (Figure 8). Although the tine

(voltage) into force data. The force data were used for the calculation of the soil penetration resistance as expressed by Eq. (1) (ASABE, 2002):

$$SPR=F\div A \quad (1)$$

where *SPR* is the soil penetration resistance (MPa), *F* is force (N), and *A* is base area (mm^2).

The root growth started to slow after exceeding the soil strength resistance at about 1 MPa, then decreased almost linearly and stopped at a resistance of about 5 MPa (Taylor et al., 1966; Bengough and Mullins, 1990; Materechera et al., 1991), and it was reported that the penetration of almost all cotton roots declined while resistance increased and stopped at 3 MPa. Moreover, the rate of root elongation differed depending on the crops. The soil penetration resistance reduced root elongation at a rate of 50% at 0.7 MPa in the case of cotton (Taylor and Ratliff, 1999), but at 1.1 MPa in the case of peanut production (Cockroft et al., 1969). Many researchers have revealed similar results for different crops (Taylor and Burnett, 1964; Taylor et al., 1964; Fiskell et al., 1968). Therefore, the newly developed control algorithm will allow growers of different crops to set the critical soil resistance values for monitoring the soil compaction level and depth. The soil strength limits could be gathered from the literature.

2.3. Tractor attachment and chassis

In order to mount the sensing tine to a tractor, a linkage system was designed as shown in Figure 2. The main frame of the soil profile sensor held the sensing tine. It was linked to the tractor by a parallelogram mechanism, which allowed the sensor to adapt itself to the variations of the surface soil.

Figure 8. Static calibration tests for force measurement.

consisted of twelve tips, in the calibration process eight of them were engaged, starting from the lower part of the tine. The upper part of the soil profile had cultivation operations during the vegetation development of the crops. The depth of the tillage operation ranged from 5 to 20 cm. Therefore, the tillage operation released soil at that depth.

Dynamic conditions were simulated in the laboratory to determine whether the sensor was capable of monitoring strength variations. To determine the compacted layer depth, randomly selected loads in a range of 20–160 kg using a scaled weight were applied on each tip of the tine during the tests and the output loads (derived from the output voltage) were recorded (Figure 9). Different scenarios were constructed in order to evaluate the performance of the sensors in terms of determining the hardpan depth for various crop types.

2.4. Programmable logic controller and control unit elements

A PLC and electronic components (Table) were used to gather data from each tip (load cell), monitor data flowing from them, and benchmark them individually with a critical root limiting value (Figure 10). The Phoenix Contact Company supplied electronic components and software.

2.5. Operating system

The operating program for the sensing system was compiled in PC WORX BASIC LIC and uploaded to the PLC unit. The operating program received the signals and recorded them individually at 0.1-s intervals, then calculated the median and created a new array for the load cells. Finally, it found the force on the load cells that exceeded the input strength limit. The depth of each critical point was calculated by using load cell identities. The hardpan depth for subsoiling operations was determined by selecting the lower levels of the depths.

3. Results and discussion

3.1. Static tests

An initial test was conducted in order to verify the performance of the load cells so that any assembly mistakes would not create further errors in measurements and lead to incorrect monitoring of the hardpan strength and depth calculation. The data relevance between the input load and the output load (derived from the output voltage) was analyzed after assembling the sensor tips into the sensor tine. The eight calibrated weights (20, 40, 60, 80, 100, 120, 140, and 160 kg) were loaded and unloaded one by one on each sensor tip. The forces applied by the weights were 0.20, 0.39, 0.59, 0.78, 0.98, 1.18, 1.37, and 1.57 kN, respectively The use of scaled weight was limited at 160 kg (1.57 kN) due to loading challenges on the pin.

The static test data revealed the consistency of the sensor tips with a higher R^2 value in terms of the input load – output load (derived from the output voltage) harmony (Figure 11). The R^2 value ranged between 0.98 and 0.99 and the calibration functions were in linear format. The data revealed the success in the manufacturing process.

Figure 9. Loading sensors for dynamic tests.

3.2. Dynamic tests

Dynamic conditions were simulated in the laboratory to see if the sensor was capable of monitoring the strength variation and determining the compacted layer. Randomly selected loads were applied on each tip of the tine based on an arbitrary amount during the realization of scenarios and were recorded in the range of 0–10 kN using a scaled weight (0–160 kg) and the output load (derived from the output voltage). Several test scenarios revealed that the sensor and its program was capable of monitoring and determining the hardpan depth. The first scenario determined the hardpan depth for cotton by setting the CI value at 1 MPa (Taylor and Ratliff, 1999). Based on the sensor measurements and program calculations, the hardpan layer was determined to be 30 cm (Figure 12). The extended scenario determined the hardpan depth if there was more than one value exceeding the CI setting limit. Based on the sensor measurements and program calculations, the hardpan layer was determined to be 38 cm (Figure 13).

The second scenario determined the compacted layer depth for peanuts by setting the value at 1.2 MPa (Cockroft et al., 1969). Based on the sensor measurements and program calculations, the hardpan layer was determined

Table. List of control unit elements and devices used in building the sensor.

Devices/tools	Technical data
TP 3070T Touch Panel	17.78 cm (7.0”) graphics-capable TFT display, 65,535 colors, 800 × 480 pixels, 1× Ethernet, 2× USB and integrated runtime of the Visu+ visualization software
ILC 130 ETH Inline Controller	Ethernet interface for coupling to other controllers and systems, with programming options according to IEC 61131-3, complete with connector and labeling field
IB IL SGI 2/F-PAC	Inline analog strain gauge input terminal, complete with accessories (connector and labeling field), two fast inputs, 4-, 6-conductor connection method
EC-E 1A DC24V	Electronic circuit breaker, nominal current: 1 A
MINI-PS-12- 24DC	DC-DC converter, primary switched mode, slim line design, input: 12–24 V DC, output: 24 V DC / 1 A
PC WORX BASIC LIC	Software package

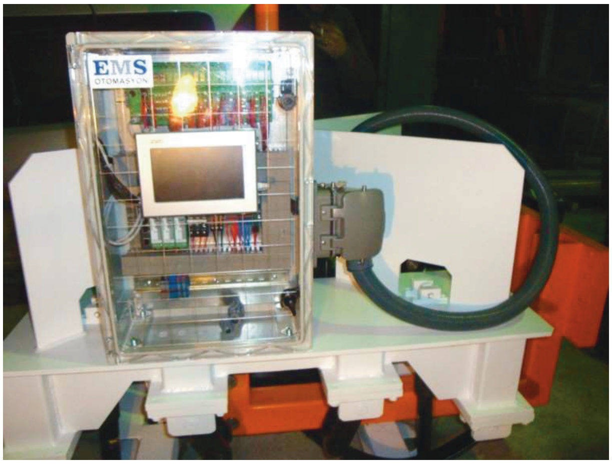

Figure 10. Electronic system of the sensor (PLC).

to be 34 cm (Figure 14). The extended scenario determined the hardpan depth if there was more than one value exceeding the CI setting limit. Based on the sensor measurements and program calculations, the hardpan layer was determined to be 30 cm (Figure 15).

3.3. Conclusions

This study focused on the sensing aspect of a variable depth tillage system, which could monitor soil compaction vertically and determine the hardpan layer on the go, and then adjust the operation depth of the tillage equipment for subsoiling. The sensor prototype was designed, built, and validated under laboratory conditions.

The sensor consisted of a tine, tractor attachment and chassis, and a data acquisition system. The tine engaged tips that connected the load cells individually for measuring the soil resistance. The sensor could operate at a maximum depth of 46 cm. The manufactured chassis carried the tine and was attached to the tractor using a constructed part. The static and dynamic tests validated that the sensor could be used to monitor soil strength variations vertically in a soil profile of 46 cm in depth. The sensor will allow us to build a variable depth tillage system.

Acknowledgments

This research was funded (No. 2011-ZRF-016) by the Scientific Research Projects Division of Ege University. The project team members included the agricultural engineer Herfeh Nasim Sedaghat, who received a Master’s degree from the Ege University Graduate School of Natural and Applied Sciences in İzmir, Turkey, in 2012. The authors would like to thank Herfeh Nasim Sedaghat, the Çelsan Agricultural Equipment Industry Company (Manisa, Turkey, email: celsan@celsan.com), Phoenix Contact GmbH & Co. KG (Germany), and Kaygan Makina Sanayi (İzmir, Turkey, email: info@kamaksan.com) for their support during the manufacturing stage of this study.

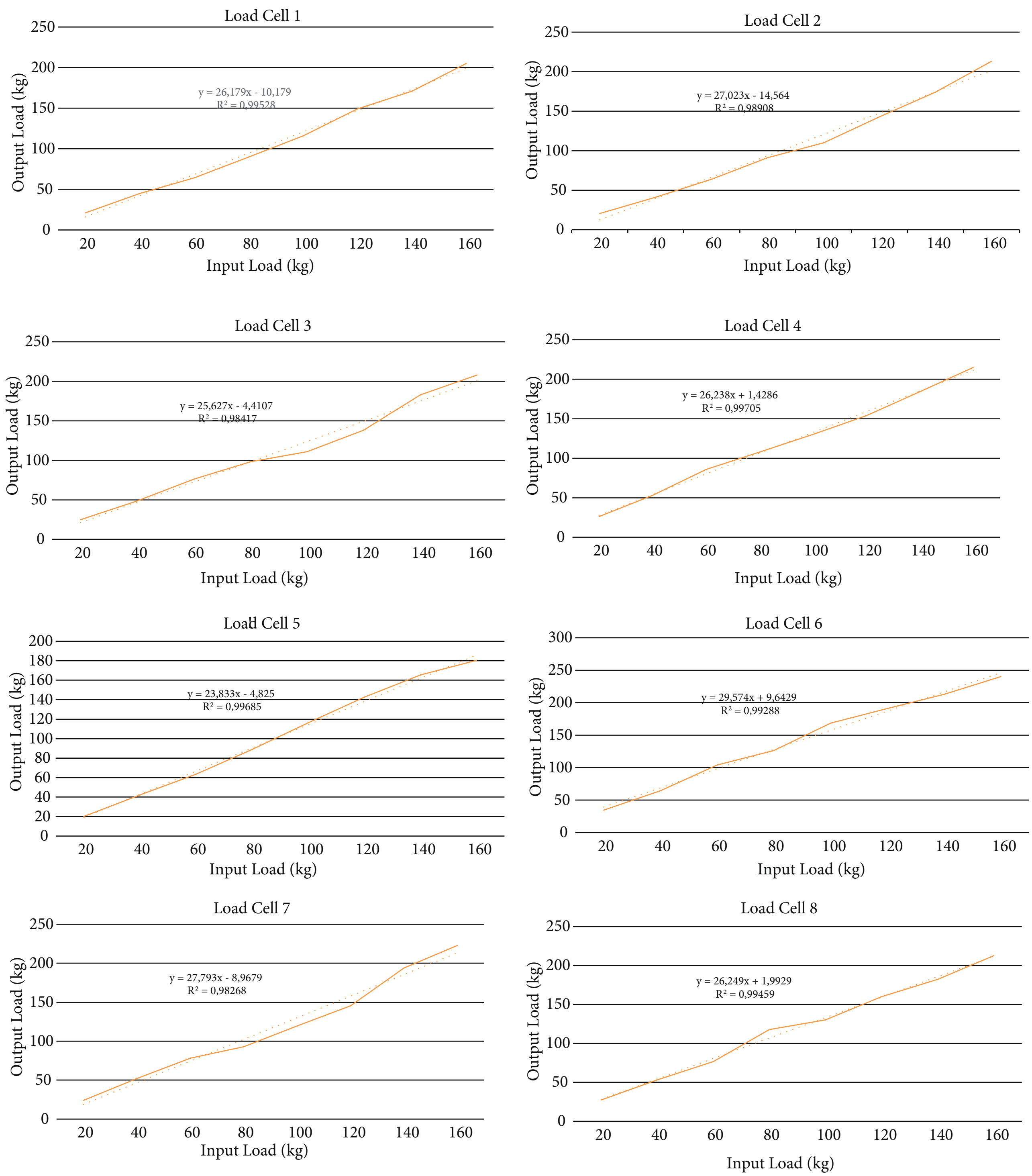

Figure 11. The relationship between the input load and output loads.

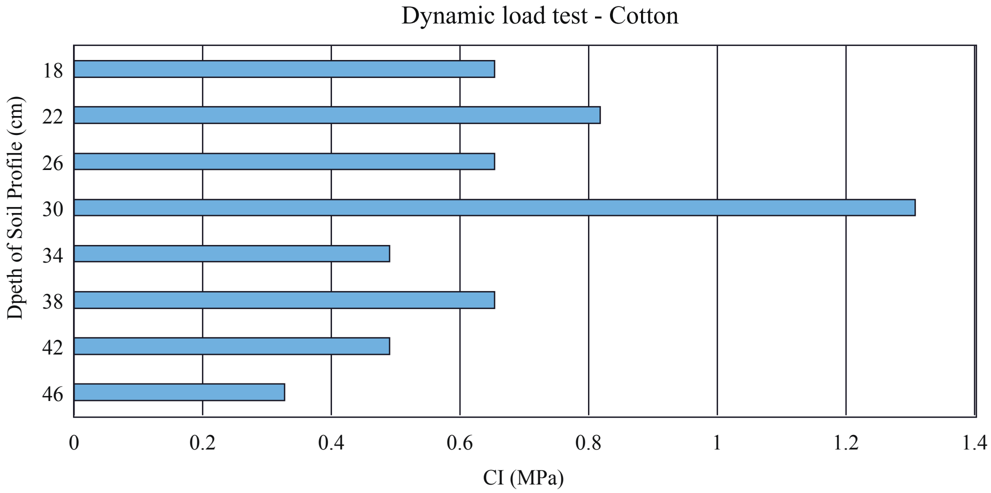

Figure 12. Dynamic load test - scenario 1.

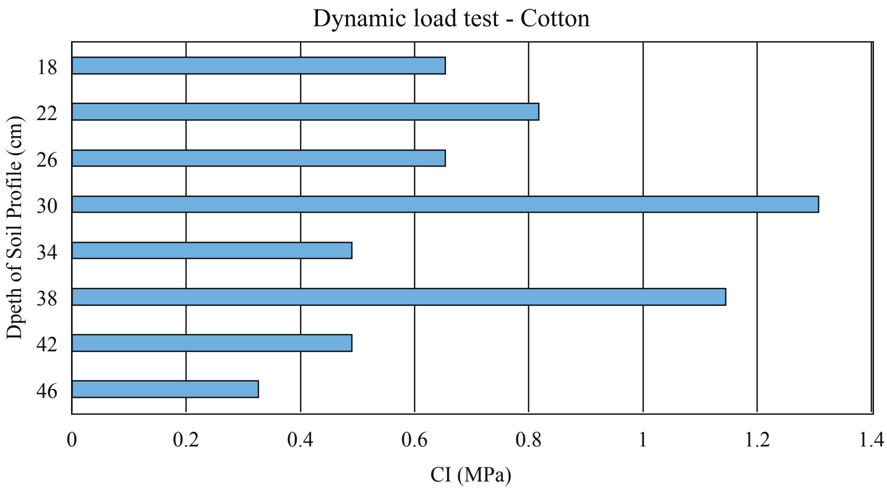

Figure 13. Dynamic load test - scenario 1.

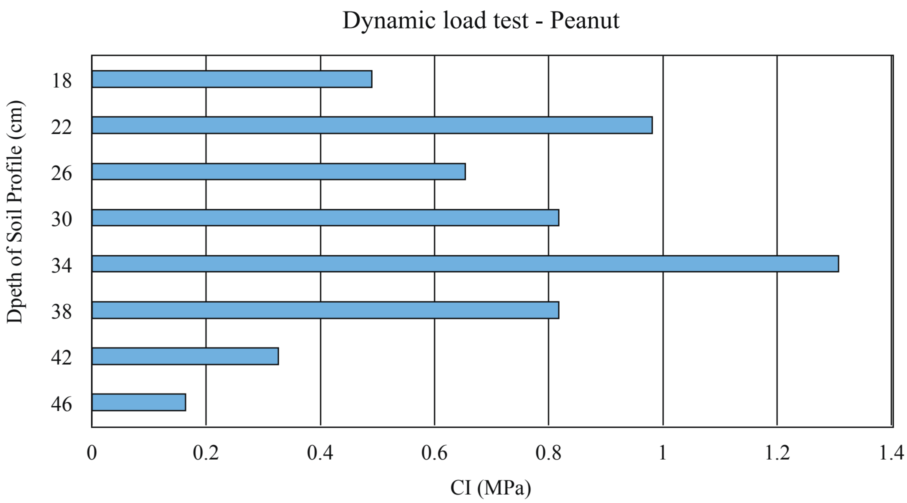

Figure 14. Dynamic load test - scenario 2.

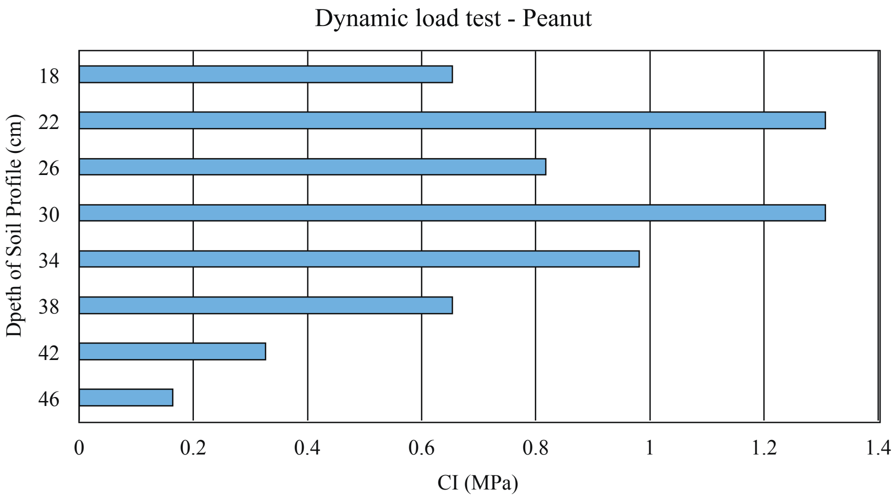

Figure 15. Dynamic load test - scenario 2.

References

Alimardani R (2005). Design and construction of a tractor mounted penetrometer. Journal of Agriculture & Social Sciences 1: 297-300.

ASABE (2010). ASABE Standards: Standards Engineering Practices Data. St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers.

ASAE (2002). ASABE Standards: Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer (EP542). St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers.

ASAE (2004). ASABE Standards: Standards Engineering Practices Data. St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers.

Bengough AG, Mullins CE (1990). Mechanical impedance to root growth: a review of experimental techniques and root growth responses. J Soil Sci 41: 341-358.

Çakır E, Gülsoylu E, Yalçın H, Aykas E (2007). Soil compaction: causes, consequences, solutions and effects on Turkish farming system. In: Proceedings of Soil Dynamics Workshop, 14–15 June 2007, İzmir, Turkey. İzmir, Turkey: Agricultural Machinery Department of Ege University, pp. 47-58.

Chukwu E, Bowers CG (2005). Instantaneous multiple-depth soil mechanical impedance sensing from a moving vehicle. T ASAE 48: 885-894.

Chung SO, Sudduth KA (2003a). Modeling Soil Failure Caused by Prismatic and Conical Tools. ASAE Paper No. 031028. St. Joseph, MI, USA: ASAE.

Chung SO, Sudduth KA (2003b). Characterization of Soil Strength Data for an On-the-Go Sensor. ASAE Paper No. MC03203. St. Joseph, MI, USA: ASAE.

Chung SO, Sudduth KA (2006). Soil failure models for vertically operating and horizontally operating strength sensors. T ASABE 49: 851-863.

Chung SO, Sudduth KA, Hummel JW (2003). On-the-Go Soil Strength Profile Sensor Using a Load Cell Array. ASAE Paper No. 031071. St. Joseph, MI, USA: ASAE.Chung SO, Sudduth KA, Hummel JW (2006). Design and validation of an on-the-go soil strength profile sensor. T ASABE 49: 5-14.

Chung SO, Sudduth KA, Motavalli PP, Kitchen NR (2004a). Relating On-the-Go-Soil Strength Data to Cone Index. ASAE Paper No. MC04205. St. Joseph, MI, USA: ASAE.

Chung SO, Sudduth KA, Plouffe C, Kitchen NR (2004b). Evaluation of an On-the-Go Soil Strength Profile Sensor Using Soil Bin and Field Data. ASAE Paper No. 041039. St. Joseph, MI, USA: ASABE.

Chung SO, Sudduth KA, Tan J (2005). Variability Structure of On-the-Go Soil Strength Sensor Data. ASAE Paper No. 051039. St. Joseph, MI, USA: ASABE.

Cockroft B, Barley KP, Greacen EL (1969). The penetration of clays by fine probes and root tips. Soil Res 7: 333-348.

Fiskell JGA, Carlisle VW, Kaashirad R, Hutton CE (1968). Effect of soil strength on root penetration in coarse-textured soils. J Geol 1: 793-802.

Fountas S, Paraforos D, Cavalaris C, Karamoutis C, Gemtos T, Abu-Khalaf N, Tagarakis A (2013). Five-point penetrometer with GPS for measuring soil compaction variability. Comput Electron Agr 96: 109-116.

Fulton JP, Wells LG, Shearer SS, Barnhisel RI (1996). Spatial Variation Of Soil Physical Properties: A Precursor to Precision Tillage. ASAE Paper No. 96-1012. St. Joseph, MI, USA: ASAE.

Gaultney LD (1989). Prescription Farming Based on Soil Property Sensors. ASAE Paper No. 89-1036. St. Joseph, MI, USA: ASAE.

Goodson R, Letlow R, Rester D, Stevens J (2000). Use of precision agriculture technology to evaluate soil compaction. In: Proceedings of the 23rd Annual Southern Conservation Tillage Conference for Sustainable Agriculture, 19–21 June 2000, Monroe, LA, USA, pp. 23-30.

Hemmat A, Adamchuk VI (2008). Sensor systems for measuring soil compaction: review and analysis. Comput Electron Agr 63: 89-103.

Khalilian A, Han YJ, Dodd RB, Sullivan MJ, Gorucu S, Keskin M (2002). A Control System for Variable Depth Tillage. ASAE Paper No. 021209. St. Joseph, MI, USA: ASAE.

Kumar M, Dadhich H, Dahich SM (2015). Development of a tractor operated soil compaction measurement device. In: Proceedings of International Conference on Technologies for Sustainable Development, 4–6 February 2015, Mumbai, India, pp. 1-4.

Materechera SA, Dexter AR, Alston AM (1991). Penetration of very strong soils by seedling roots of different plant species. Plant Soil 135: 31-34.

Perumperal JV (1987). Cone penetrometer applications-a review. T ASAE 30: 939-944.

Raper RL (2003). Soil Compaction Management. 1st ed. Encyclopedia of Agricultural, Food, and Biological Engineering. Boca Raton, FL, USA: CRC Press.

Raper RL, Washington BH, Jarrell JD (1999). A tractor-mounted multiple-probe soil cone penetrometer. Appl Eng Agric 15: 287-290.

Sedaghat HN (2012). Designing an (on the go) soil strength sensor to determine the hardpan depth. MSc, Ege University, İzmir, Turkey.

Smith CW (2007). An Automatic Depth Control System for the On-the-Go Soil Strength Sensor. Auburn, AL, USA: Auburn University.

Sun Y, Lin J, Ma D, Zeng Q, Schulze Lammers P (2007). Measurement of penetration force using a Hall-current-sensor. Soil Tillage Res 92: 264-268.

Taylor HM, Burnett E (1964). Influence of soil strength on the root-growth habits of plant. Soil Sci 98: 174-180.

Taylor HM, Locke LF, Box JE (1964). Pans in southern Great Plains soils III. Their effects on yield of cotton and grain sorghum. Agron J 56: 542-545

Taylor HM, Ratliff LF (1999). Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci 108: 113-119.

Taylor HM, Roberson GM, Parker JJ (1966). Soil strength and seedling penetration relations for medium to coarse-textured soil materials. Soil Sci 102: 18-22.

Tekin AB (2016). Tarım 4.0. Tokat, Turkey: Endüstri 4.0 Paneli (in Turkish).

Tekin Y, Kul B, Okursoy R (2008). Sensing and 3D mapping of soil compaction. Sensors 8: 3447-3459.

Topakci M, Unal I, Canakci M, Celik HK, Karayel D (2010). Design of a horizontal penetrometer for measuring on-the-go soil resistance. Sensors 10: 9337-9348.

Topp GC, Lapen DR, Edwards MJ (2003). Laboratory calibration, in-field validation and use of a soil penetrometer measuring cone resistance and water content. Vadose Zone J 2: 633-641.

Way TR, Kishimoto T, Torbert AH, Burt ED, Bailey AC (2007). Tractor tire aspect ratio effects on soil bulk density and cone index. In: Proceeding of Soil Dynamics Workshop, 14–15 June 2007, İzmir, Turkey. İzmir, Turkey: Agricultural Machinery Department of Ege University, pp. 27-47.

Wells L, Stombaugh TS, Shearer SA (2003). Crop yield response to precision deep tillage. T ASABE 48: 895-901.