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Development of a Real-Time Measurement System for Horizontal Soil Strength

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Abstract

Purpose: Accurate monitoring of soil strength is a key technology applicable to various precision agricultural practices. Soil strength has been traditionally measured using a cone penetrometer, which is time-consuming and expensive, making it difficult to obtain the spatial data required for precision agriculture. To improve the current, inefficient method of measuring soil strength, our objective was to develop and evaluate an in-situ system that could measure horizontal soil strength in real-time, while moving across a soil bin. **Methods:** Multiple cone-shape penetrometers were horizontally assembled at the front of a vertical plow blade at intervals of 5 cm. Each penetrometer was directly connected to a load cell, which measured loads of 0–2.54 kN. In order to process the digital signals from every individual transducer concurrently, a microcontroller was embedded into the measurement system. Wireless data communication was used between a data storage device and this real-time horizontal soil strength (RHSS) measurement system travelling at 0.5 m/s through an indoor experimental soil bin. The horizontal soil strength index (HSSI) measured by the developed system was compared with the cone index (CI) measured by a traditional cone penetrometer. **Results:** The coefficient of determination between the CI and the HSSI at depths of 5 cm and 10 cm (r^2 = 0.67 and 0.88, respectively) were relatively less than those measured below 20 cm ($r^2 \geq 0.93$). Additionally, the measured HSSIs were typically greater than the CIs for a given numbers of compactor operations. For an all-depth regression, the coefficient of determination was 0.94, with a RMSE of 0.23. **Conclusions:** A HSSI measurement system was evaluated in comparison with the conventional soil strength measurement system, CI. Further study is needed, in the form of field tests, on this real-time measurement and control system, which would be applied to precision agriculture.

Keywords: Cone index, Horizontal soil strength, Measurement, Real time processing, Sensor

Introduction

Soil is a basic element of agriculture, and a variable that is very important for crop growth, environments, and agricultural machine design and use. Plowing and harrowing make soil environments suitable for crop growth. These tasks are essentially performed for agricultural production, despite the fact that great amounts of energy are needed, because these efforts greatly affect crop growth. International crude oil prices have increased rapidly due to the political instability in the Middle East and North Africa regions. Moreover, oil prices have been steadily increasing due to the imbalance between supply and demand resulting from the production quota of the Organization of Petroleum Exporting Countries (OPEC) that has been continuously maintained at low levels. Long-term prospects of oil prices indicate increases to USD92.50 per barrel by 2020 and to USD187 per barrel by 2030 (KNOC, 2010). Therefore, to be prepared for oil price increases, high-efficiency agricultural machines should be developed as an energy-saving measure, and tractor-

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plowing energy-saving technologies that can maximize tractor fuel efficiency should be studied.

The average engine power consumption for plow plowing, rotavator plowing, baler work, and wrapping work among farming work using tractors in South Korea was analyzed; the resultant values were 35.4, 48.5, 46.3, and 20.7 kW, respectively, indicating that the largest amount of power is consumed during rotavator plowing (Lee, 2011).

However, most farmers in South Korea omit primary plowing work and only perform rotavator work that implements primary and secondary plowing simultaneously. Therefore, work efficiency should be enhanced and plowing energy should be saved through appropriate operation of tractors during the rotavator plowing work that consumes the largest amount of power among farming tasks. During plowing work using tractors, the traction efficiency of tractors varies greatly according to the physical conditions of the soil, the plowing depth of the implement, and the running speed of the tractor (Park, 2009). In particular, if the plowing depth of plowing implements such as plows and rotavators is adjusted to be too deep, energy losses will occur due to increases in the tractor traction power and the tire slip phenomenon. On the contrary, if the plowing depth of the implement is too shallow, appropriate work efficiency cannot be obtained owing to incomplete soil inversion and destruction. Therefore, to solve such problems, hitch control systems are used in agricultural tractors to appropriately adjust the plowing depth of implements according to soil conditions, thereby enhancing traction and work efficiency. However, most plowing studies are related to plows and no studies have been conducted yet on rotavator plowing depth control systems based on real-time soil data.

Graded plowing methods that control plowing depth according to the soil conditions of the farmland are regarded as capable of greatly reducing the energy required for plowing, compared to conventional plowing methods. In general, as plowing depth and soil strength increase, the energy required for plowing also increases. Therefore, to save plowing energy, the plowing depth should be continuously controlled during plowing, based on first-hand information on soil strength in the farmland. To this end, the development of a real-time soil hardness data collection system is essential; a tractor load control system linked to the foregoing system should be also developed.

Researchers have studied sensors and methods that can measure soil strength. The primary tool used to quantify soil strength by depth, and thereby provide information related to soil compaction and morphological characteristics, is the cone penetrometer. The index of soil strength measured by a cone penetrometer, the cone index (CI, in MPa), is defined as the force per unit base area required to push the penetrometer through a specified small increment of soil (ASABE, 2013).

The CI value was utilized to predict traction power and plowing resistance (Lee et al., 2009; Park, 2009; Park et al, 2012). To collect more CI data, a digital soil cone index measuring device was developed for replacing the conventional analog device (Lee et al., 2010). Because it is difficult to collect enough penetrometer data to adequately describe within-field compaction variations, several on-the-go, horizontally-operating soil strength sensors have been developed (Hall and Raper, 2005; Chung et al., 2006). Hall and Raper (2005) developed an on-the-go soil strength sensor (OSSS) that can measure soil strength at different depths. The device had a single sensor mounted on the leading edge of a shank while it passed horizontally through the soil. They used 30° prismatic sensing tips with a flush-mounted 625 mm^2 impedance, an extended 625 mm^2 impedance, and a 2500 mm^2 impedance, and defined the wedge index (WI) as the measured force divided by the base area of the tips. Chung et al. (2006) developed a sensor, called the soil strength profile sensor (SSPS), which measured soil strength to a 50 cm depth at 10 cm increments. The cutting forces of five prismatic tips that extended in front of the main blade were measured by load cells as the tractor- mounted device moved through the soil. They defined the prismatic soil strength index (PSSI, MPa) as the force measured by the SSPS divided by the base area of the prismatic tip, making it comparable to the CI (MPa) of a cone penetrometer. Field research (Chung et al., 2008) showed that the soil strength measured by this sensor was affected by soil water content, bulk density, and texture. The best results were obtained when the depth of operation was included in the model relating soil strength to soil properties, or when analysis was conducted within a single depth. Although these sensors (Hall and Raper, 2005; Chung et al., 2006 and 2008) have been able to provide on-the-go soil strength data, there is a need to collect data in real-time for applications such as sensor networks and decision-making directly while operating in the field.

Therefore, the objective of this research was to develop and evaluate an in-situ system that could measure horizontal soil strength at multiple depths in real-time.

Materials and Methods

Design and fabrication of the measurement system

Concept of the measurement system

Figure 1 shows the concept of the real-time measurement system for horizontal soil strength (RHSS) developed in the present study. As with soil cone penetrometers, the RHSS is equipped with many sensor tips at different depths for soil strength measurement by depth, and is attached to a running body, such as a tractor, to measure horizontal penetration resistance in real-time while the running body traverses the farmland. Consequently, the RHSS can measure the soil strength information of the farmland in real-time so that the plowing depth can be continuously controlled during plowing, and soil strength maps by location in the farmland can be obtained for various depths. Values obtained by dividing the penetration resistance (in N) measured by the RHSS by the cross-sectional area of the sensor tip were defined as the horizontal soil strength index (HSSI; in MPa).

Design of the measurement system

Major design factors in the development of the RHSS were determined to be the maximum measurement depth, the range of measurement of penetration resistance, the tip shape, and the tip spacing. The maximum measurement depth and the range of measurement of penetration resistance were determined through a review of the cone penetration resistance profile of soil in South Korea reported in literature. The tip shape and spacing were determined through a review of similar studies (Hall and Raper, 2005; Chung et al., 2006) and the cone penetration resistance profile of soil in South Korea. In most farmland, the CI values showed a tendency to increase with increasing depth to a certain depth, and then to decrease thereafter.

When the CI profile review results were put together, it could be seen that the peak of the rhizosphere portion of CI values, which are a major matter of concern in crop cultivation, appeared within a depth of 30 cm, and that the maximum value was 3.9 MPa.

Considering these results, the maximum measurement depth of the real-time measurement system for horizontal soil strength developed in the present study was determined to be 50 cm, and the maximum range of measurement of the HSSI was determined to be 10 MPa.

RHSS sensor tip shape and spacing were also determined through a review of existing cases from similar studies. Based on the results of this review, the linear regression equations of sensor tip shape and tip spacing for the CI generally showed significant correlations, although a small difference existed between sensor tip shape and tip spacing, and good results were obtained when sensor tips protruded from the housing in which they were installed and tip spacing was secured.

The shapes of the penetration tips designed in the present study are as shown in Figure 2. A shape with a cone penetration angle of 30°, which is presented in ASABE S313.3, was adopted. The diameter of the base of the cone was chosen as 18 mm, which is smaller than the

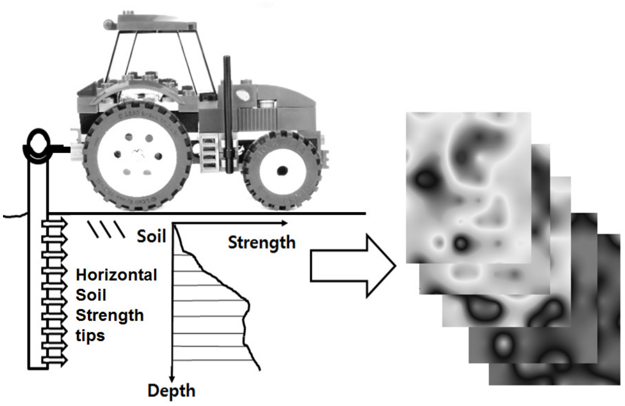


Figure 1. Operational concept of the real-time measurement system for horizontal soil strength: field data collection using the sensors, and resultant multi-layered soil strength map (Chung et al., 2006).

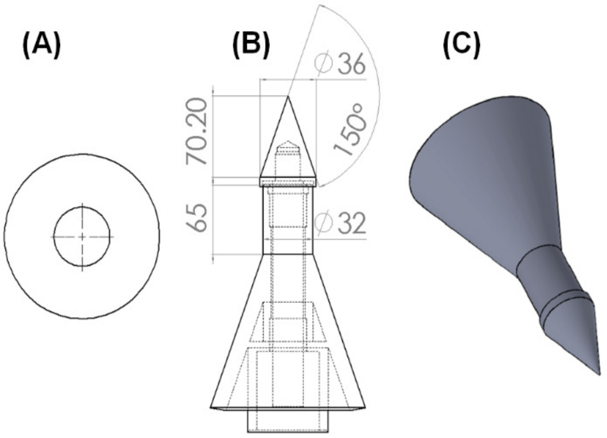


Figure 2. Schematic diagram of the RHSS sensing tip: front view (A), top view (B), rendered isometric view (C) (unit: mm).

20.27 mm cone presented in ASABE S313.3, but larger than the 12.83 mm cone presented in the same standard. The cross-sectional area of the underside of the cone was determined to be 254 mm^2, which is in between the large cone (323 mm^2; ASABE, 2013) and the small cone (129 mm^2; ASABE, 2013) in the ASABE standard. The tip shaft diameter was chosen as 16 mm, which is smaller than the 18 mm tip diameter by 2 mm to minimize the frictional force that may be generated on the shaft when the soil's horizontal resistance is measured. Stainless steel (STA301 series) was used as the sensor tip material.

The spacing of the sensor tips determined by Chung et al. was 10 cm, to measure the profile of soil strength (2006). To determine the appropriate tip spacing for this study, CI profiles that were studied earlier in South Korea, were reviewed and analyzed (Park, 2009). The depth interval was measured at 5 cm on paddy fields and upland. A smaller sensor tip spacing has the advantage of enabling the measurement of horizontal penetration resistance at more depths, but is more costly. Although larger tip spacing is less costly, it has the disadvantage of a higher possibility of being unable to sense changes in soil strength according to depth. Based on the results of analysis, the sensor tip spacing for the present study was determined to be 5 cm, because this tip spacing was judged to enable good detection of the degree of changes in the CI profiles at diverse depths. Since the diameter of each sensor tip is 18 mm, the space between sensor tips is 32 mm.

Load cell

Since the base cross-sectional area of the tip of the RHSS developed in the present study is 254 mm^2, if the maximum expected soil strength of arable soil strata in South Korea is assumed to be 10 MPa, the maximum force measured at each tip is 10 MPa × 254 mm^2 = 2.54 kN. From among commercially available load cells, a load cell with a measurement region diameter of 4 mm (CMM2, Dacell, Cheongju, Chungbuk, Korea) was selected. This sensor has a full-bridge circuit in which four strain gauges are connected to each other. It can measure loads in a working temperature range of –20 to +70°C, its nonlinearity is 1.0%, its hysteresis is 1%, and its repeatability (precision) is 99%. It can measure loads ranging from 0 to 4.9 kN with not more than 1% of the measurement output power.

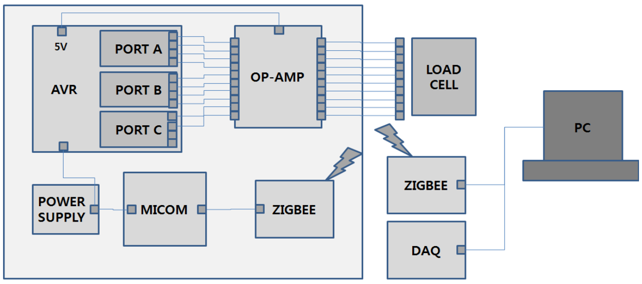


Figure 3. Schematic diagram explaining the procedures of signal processing and data acquisition from the load cell.

Signal processing and monitoring

The output values of the load cells connected to individual sensor tips of the measurement system for horizontal soil strength were given as minute analog signals. However, if these from the load cells were used as they were, accurate data values would not be secured owing to noise and losses occurring during signal processing and transmission. Therefore, a module capable of amplifying and filtering these minute analog signals had to be configured. Figure 3 shows a schematic of a load cell signal processing module, and a view of the fabricated module is shown in Figure 4. This module consisted of a main processor that amplified signals inputted from load cells, removed noise through a lowpass filter, and performed A/D conversion, and a module that transmitted the processed measured value wirelessly.

The amplification module used in the present study generated output voltage values corresponding to imposed loads at the precision of 1 mV, and amplified signals up to 128 times using a built-in programmable amplifier. The module converted analog signals into digital values, since it was embedded with an A/D converter having 24-bit resolution.

When the communication speed is set to 9600 bps (bits per second), this module transmits 1200 bytes of data per second. This module transmits character strings and transmits/receives 24 packets per second, since one packet consist of 50 bytes. This is a theoretical number– and many packets are lost in the process of transmission/receiving in actual communications. Therefore, considering the packets that would be lost, the data acquisition frequency of the measurement system for horizontal soil strength of the PC, which was used as a data storage device, was determined to be 10 Hz.

The maximum measured load of the load cell selected for this study was 4.90 kN, and the output power of the

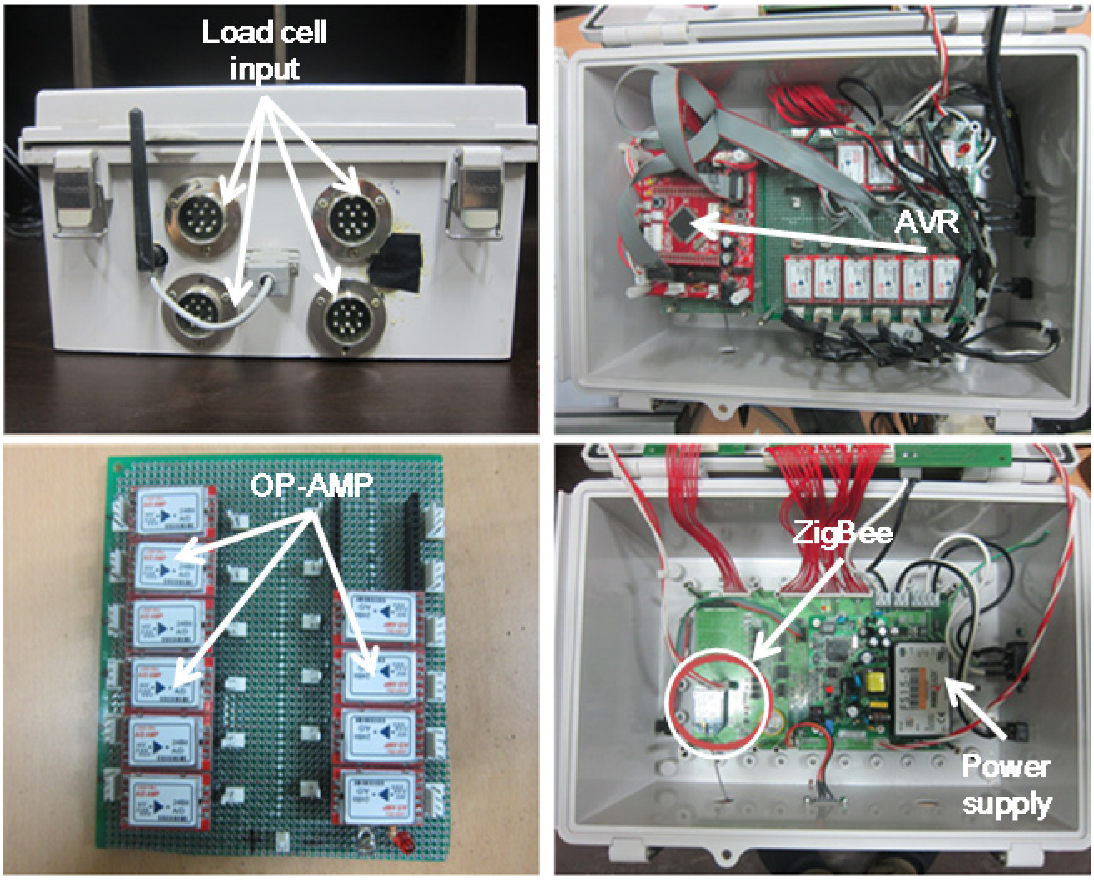


Figure 4. Photos of circuits fabricated for signal processing and data acquisition from the load cell.

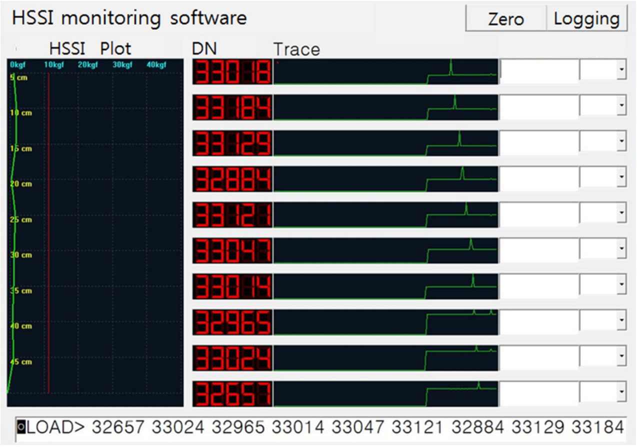
Table 1. Specifications of the microprocessor

Item	Specification	Unit	Item
Model	AB-M128-B		Model
External voltage	12	V	External voltage
Inner voltage	5	V	Inner voltage
DC output connector	5, 12	V	DC output connector
UART connector (Pin 1 – 4)	VCC, TX, RX, GND		UART connector (Pin 1 – 4)

load cell was between 0.7 mV/V at a minimum and 1.2 mV/V at a maximum.

The main CPU used as the primary processing module for collecting the digital data amplified from the individual load cells and wirelessly transmitted to the PC was an AB-M128-B (NEWTC, Seoul, Korea), a board developed based on the ATmega128 CPU of the product groups that adopted the MegaAVR of ATMEL Co. (Table 1). This microcomputer was set up with an 8-bit reduced instruction set computer structure. Its operation speed was high because it used simple commands and its code size was optimized for C and assembly languages. It was supplied with 12 V power from the outside and used 5 V single power for internal operations. It conducted serial communications (UART) since it had six ports (Port A, B, C, D, E, and F) connected with 10-pin connectors. In addition to general arithmetic operations and logical operations, it performed the functions of writing and reading data values from sensors input through the six ports, and could be integrated with additional peripheral devices for control and communication.

The application of wireless communications has recently overcome the disadvantages of wired systems, such as constraints of space and cost. Wireless technology has made it possible for processes to be monitored and data to be collated from a remote location. Wireless technology



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LOAD> 32657 33024 32965 33014 33047 33121 32884 33129 33184
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Figure 5. Screen shot of the HSSI monitoring software.

can also assist in evaluating and improving the efficiency, performance, accuracy, reliability, and energy consumption of a system. A wireless communication module was used to transmit the data processed in the microcomputer to users of PCs, etc. The Xbee-Pro module (Digi International Inc., Minnetonka, MN, USA) used in the present study is a qualified module that acquired ISO 9001:2000 certification, and adopted the ZigBee/IEEE 802.15.4 standard as a communication standard.

Figure 5 shows an application program made to observe changes in measurement subjects by illustrating signals generated by the measurement system for horizontal soil strength system in real-time. This application program was developed using Microsoft Visual C++ 6.0 (Microsoft, CA, USA), and includes a function to store measured data in the local system in the form of files, in addition to the function of illustrating signals on the screen. It illustrated the values of the soil's resistance to horizontal penetration for different measurement depths corresponding to the 5 cm spacing designed between tips as integer values digitalized with a resolution of 24 bits, which was higher than the 12-bit resolution used in an earlier study (Chung et al., 2006). In addition, a function for connecting the horizontal penetration resistance values measured in real-time at 10 different depth points with each other to organize them in the form of general HSSI graphs and illustrating them on the screen can be said to be its major function. The measurement system and the PC on which the application program was executed were connected in a combination of wired and wireless forms. RS-232 communication was implemented in the case of the wired connection, and ZigBee communication was implemented in the case of the wireless connections.

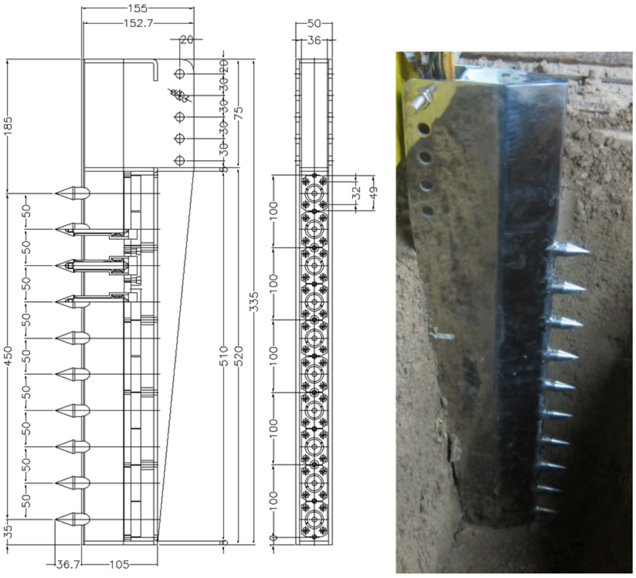

Figure 6. View of real-time horizontal soil strength device. Drawing (left) and photo (right) of the sensor and blade assembly (unit: mm).

Tip support blade

The tip blade was designed to penetrate vertically into the soil profile with minimum downward force. The tip support blade of the RHSS was modified based on previous research. To facilitate this penetration into the soil, the blade of the RHSS was beveled to 30°, the same degree that previous researchers used (Hall and Raper, 2005; Chung et al., 2006).

The width of the starting cross section of the tip support blade was designed to be 18 mm, the same as the diameter of the tip base, to reduce the amount of load applied in the direction of progress. The soil penetration angle of the cross section was designed to be 30°. To block soil inflow into the inside of the blade, and to prevent gaps that may have appeared in joint regions, the tips were welded onto support blades to make an integral form. Each tip support blade was divided into a blade part and a connecting part. The length of the blade portion of the blade was 670 mm, the width was between 18 mm at the minimum and 58 mm at the maximum, and the thickness was between 18 mm at the minimum and 50 mm at the maximum. The connecting part was made into an integral form with the blade part. The length of the connecting part was 670 mm, the width was between 47 mm at the minimum and 97 mm at the maximum, and the thickness was 50 mm. The blade and the main body were made of 5 mm thick stainless steel. In addition, 16 mm diameter holes were drilled at a total of 10 points, corresponding to the sensor positions at intervals of 50 mm from 35 mm from the bottom so that 10 sensor tips could be installed. Figure 6 shows the design drawing of the tip support blade and a photo of a fabricated tip support blade.

Sensor calibration

To calibrate the fabricated measurement system for horizontal soil strength, weights were connected to a sensor tip to apply loads to it, as shown in Figure 7. The weights applied to the sensor tip were in the range of 0–592 N with differences of 52 N. The signals outputted from the sensor were acquired for 20 s at 10 Hz.

Figure 8 shows the sensor output value (digital output, DO) for 200 s when a certain amount of force was applied. The mean and range of the signal were 33129.1 ± 2.55 (95% confidence interval) and 114, respectively. The range and standard deviation were calculated from each output dataset collected for the different acquisition channels and loadings. With a 95% confidence, the means of the ranges and standard deviations were 49.89 ± 2.55 DO and 18.39 ± 0.37 DO, respectively. From equation 1, the corresponding strength statistics were calculated as 1.2 ± 0.06 kPa and 0.47 ± 0.009 kPa, respectively. From these results, this verified that the load cells and data acquisition system were capable of recording reliable, low-noise signals for a static load.

Figure 9 shows the relationship between the force applied to the sensor tip and the HSSI. The forces acting on the sensor tips and the HSSI showed significant linear correlations within the effective measurement range; $R^2 = 0.99$ ($P < 0.0001$) and RMSE = 0.0001 MPa are shown. The relationship between the values of the horizontal penetration resistance applied to each load cell of the horizontal penetration measurement system and the HSSI is shown by equation 1:

$$\begin{aligned} &\text{HSSI (MPa)}_{\text{each tip}} \qquad (1)\\ &= 0.005 \times \text{Force (N)} / \text{Area (mm}^2) - 0.0028\\ &= 2.56 \times 10^{-5} \times \text{Digital output}_{\text{each tip}} - 8.48 \end{aligned}$$

Figure 7. Testing view for calibration of RHSS sensor output.

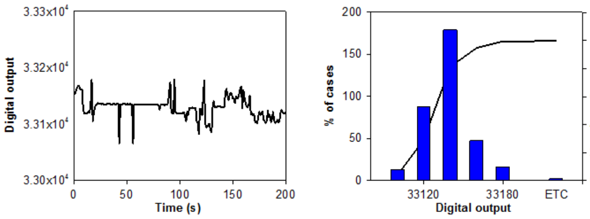

Figure 8. An example of the output signal for a static load (left), and the corresponding histogram (right).

Measurement system performance experiment

To evaluate the basic operational performance of the RHSS and the amount of change in the HSSI according to soil compaction, and to examine the relationship between

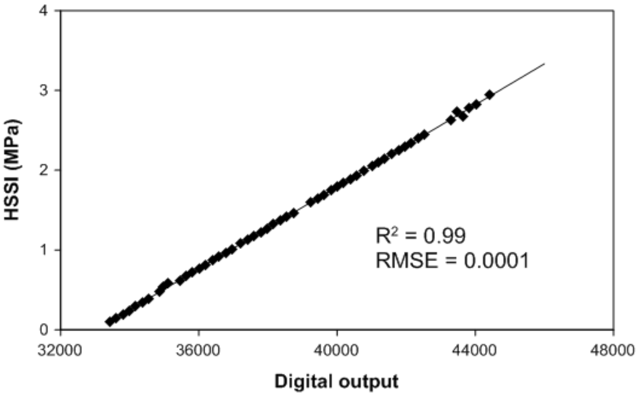

Figure 9. Results of the calibration tests relating the applied digital output and the HSSI output from each load cell.

Figure 10. Soil preparation equipment (top left), prepared soil (top right), and RHSS attachment (bottom) for soil bin performance test.

the HSSI and the CI, experiments were conducted in artificial soil bins. Since the physical characteristics of soil are different by location and experiments cannot be reproduced under the same conditions in general farmlands, in many cases experiments are conducted in artificial soil bins in order to address these shortcomings of experiments in actual farmlands.

The artificial soil bin used in the present study consisted of a soil bin, a rail system, a truck driving system, an experiment measurement truck, and a soil processing truck. The soil bin was 12 m long, 1 m wide, and 0.7 m high, and was constructed with reinforced concrete outer wall structures. The thickness of this reinforced concrete was 0.2 m. In addition, the soil bin was equipped with a draining facility so that the water content of the soil could be adjusted. A rail system was constructed on the top of the soil bin so that the soil processing truck and the experiment measurement truck could move. This rail was 150 × 75 × 5.5 × 9.5 mm and was in the form of an I-shaped steel rail (Lee et al., 1997).

Figure 10 shows a view of a performance experiment for the measurement system for horizontal soil strength in an artificial soil bin system. The measurement system for horizontal soil strength was attached to the support of a soil measurement experiment truck. A device was installed at the front of the experiment truck consisting of a reinforcing bar structure. At the front of this reinforcing bar structure were holes at intervals of 5 cm spaces, and these holes and the measurement system were connected using bolts and nuts to install the measurement system for horizontal soil strength on the experiment truck. The experiment truck was wired to a motor and was implemented so that it could be towed with a force of 10 HP. Because 10% slip occurred, the driving speed was measured as 0.5 m/s. Figure 10 shows the artificial soil bin, rail system, soil processing truck, and measurement experiment truck.

The composition and classification of the soil used in the experiment were identified according to the method of the U.S. Department of Agriculture (USDA)–the results indicated that the soil was sandy loam comprising 53.5% sand, 37.1% silt, and 9.4% clay. On the day of the experiment, the temperature was 25°C and humidity was 34%. The water content in the soil was 13%, and was measured using the 130°C, 36-hour drying method under ASABE Standards, S358.2 (ASABE, 2012).

The relationships between the basic performance of the RHSS and HSSI and CI according to the degree of soil

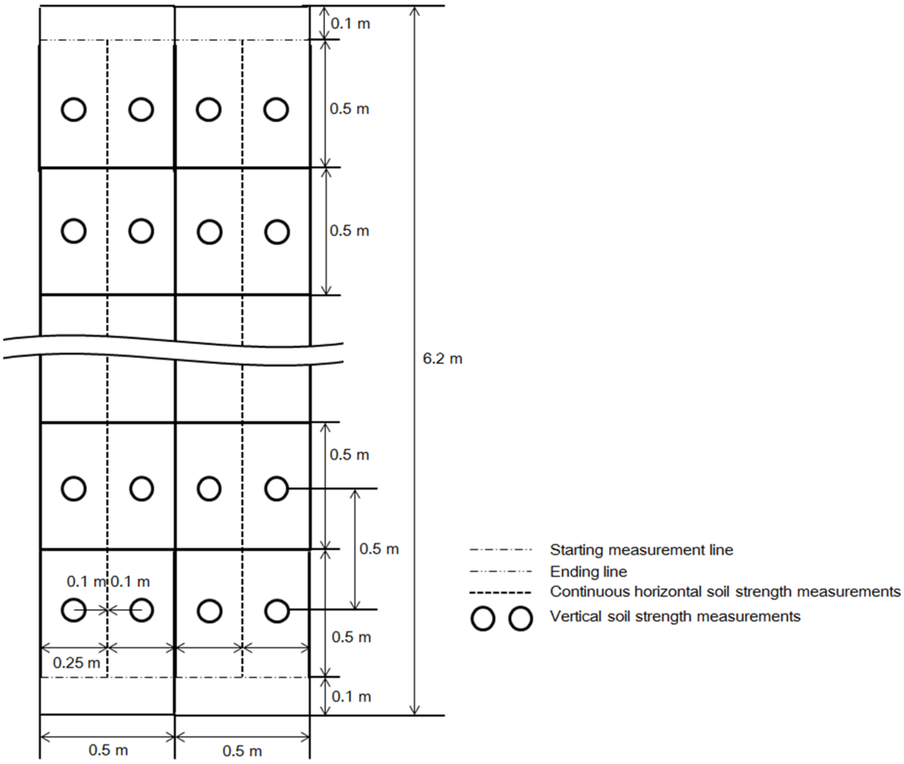

Figure 11. Experimental plot layout for HSSI and CI measurement in the soil bin.

compaction in the artificial soil bin and sensor tip depths were reviewed. First, whether the soil's horizontal penetration resistance sensor had any problems with measuring when it was driven into soil was checked. Second, the degree of change in the HSSI according to the degree of soil compaction, which changed according to the number of roller compactor operations, was identified. Finally, the degree of change in HSSI according to depth was checked. Soil conditions were created through changes in the number of times the soil compacting roller was used (1, 3, 7, and 9 times). It was assumed that as the number of times of roller driving increased, the level of soil compaction would increase, leading to higher values for the penetration resistance of the soil.

Figure 11 shows the method that was used to measure the horizontal penetration resistance in the artificial soil bin. The width of 1 m was divided into two sections to measure horizontal penetration resistance two times at an interval of 50 cm. Once horizontal penetration resistance measurement has started, soil is crushed by the blade, and vertical penetration resistance cannot be measured at the point of crushing. Therefore, before the horizontal penetration resistance measurement test started, vertical penetration resistance was measured at positions 10 cm away from the horizontal penetration resistance measurement path on both sides at intervals of 50 cm in a 6-m-long section, i.e., 13 times per side, or 26 times in total. Then, the average of the two vertical penetration resistance values measured on the two sides was used. The shape of the vertical cone penetrometer used for the CI measurement is shown in Figure 12.

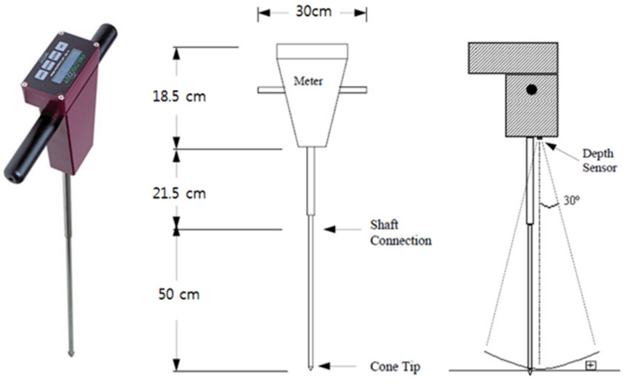

Figure 12. Photo (left), dimensions (middle), and schematic (right) of the cone penetrometer.

Results and Discussion

Figure 13 shows the results of the measurement of the HSSI and the CI after the soil was compacted by operating the compacting roller nine times during soil processing. The HSSI and the CI showed similar trends of changes in the direction of the running RHSS, and it was identified that as the depth increased, all penetration resistance values increased. Both the CI and HSSI values decreased at the final portion of the experimental measurement. This was judged attributable to the fact that the processing device did not compact the soil properly in that region, as it was close to the end of the soil bin. Table 2 shows the mean values and standard deviations at individual depths, for each number of roller operations. When the number of roller operations was nine, the standard deviation of the values measured using the measurement system for the CI and the HSSI were below 0.47 and 0.38 MPa, respectively, for all sections corresponding to individual depths. However, when the number of roller operations was below seven, the soil compaction was not sufficient for testing soil strength. For the comparison of the HSSI and the CI, therefore, it was necessary to operate the roller seven times or more. There was some difference in soil strength measured by the RHSS and the cone

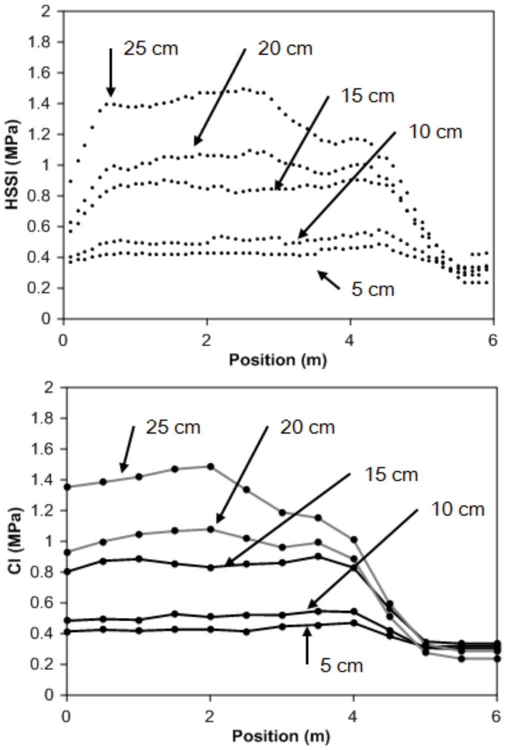

Figure 13. Scatter plots of the HSSI and the CI after 9 roller operations.

Table 2. CI and HSSI mean and standard deviation (SD) for each roller operation

No. of operating roller	Soil strength (MPa)		Depth (cm)					
			0	5	10	15	20	25
1	CI	Mean	0.03	0.03	0.03	0.03	0.03	0.03
		SD	- [a]	-	-	-	-	-
	HSSI	Mean	0.25	0.36	0.33	0.32	0.30	0.32
		SD	0.03	0.02	0.01	0.01	0.01	0.01
3	CI	Mean	0.04	0.15	0.15	0.15	0.15	0.15
		SD	-	-	-	-	-	-
	HSSI	Mean	0.26	0.37	0.34	0.032	0.29	0.32
		SD	0.01	0.01	0.01	0.01	0.01	0.01
7	CI	Mean	0.33	0.35	0.42	0.58	0.75	0.79
		SD	0.02	0.05	0.08	0.15	0.20	0.29
	HSSI	Mean	0.42	0.42	0.52	0.62	0.67	0.74
		SD	0.03	0.05	0.09	0.12	0.14	0.17
9	CI	Mean	0.27	0.40	0.46	0.71	0.79	1.02
		SD	0.01	0.08	0.09	0.23	0.34	0.47
	HSSI	Mean	0.27	0.41	0.48	0.76	0.86	1.13
		SD	0.01	0.04	0.06	0.18	0.27	0.38

[a] SD value was below 0.005

penetrometer at a depth of 25 cm (Figure 13). The collected data was delayed when the RHSS was just inserted into the soil, and while it traveled 50 cm in the direction of movement.

Figure 14 shows the HSSI values measured at a depth of 25 cm, according to the number of times of processing by the compacting roller, which is a soil processing device. It can be seen that as the number of times of processing by the roller increased, penetration resistance values increased because of soil compaction by the roller.

HSSI values changed little between one and three times of processing by the compacting roller but changed greatly at seven times of processing. Although the degrees of changes in HSSI and CI values were similar when the number of times of processing by the roller was nine, an error close to 1 m was judged to have occurred. Given this, if the values are corrected using the section average method shown in Figure 14, a relational expression that is highly precise in describing the relationship between the HSSI and the CI can be derived.

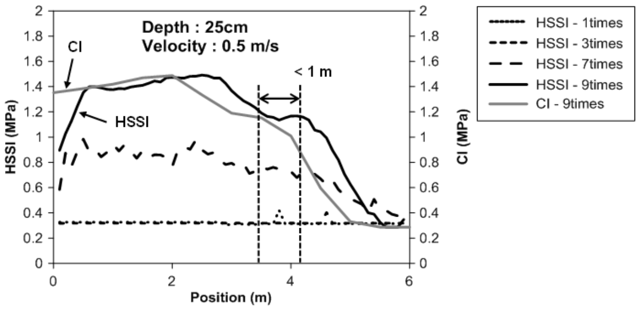

Figure 14. Scatter plots of the HSSI after 1, 3, 7, and 9 roller operations.

Figure 15 shows the mean values of the CI at 5 cm depth intervals obtained experimentally, in comparison with the mean values of the HSSI measured for a running distance of 1 m to correct the values. A dataset of five depths (5 to 25 cm, at 5 cm intervals) and 12 positions (0 to 6 m, interval 0.5 m) were used for correlating to the CI and the HSSI. The CI was collected at 2.5 cm intervals, when the inserted speed was 2.5 cm/s. The HSSI was collected at 10 Hz with a track speed of 0.5 m/s. The collected CIs and HSSIs were moving-averaged with each 5 cm and 1 m interval, as shown in Figure 15.

Plots of the HSSI versus the CI showed a linear, positive relationship (Figure 16). On reviewing Figure 16, it can be seen that the data are close to the 1:1 line. Table 3 sets forth the results of the evaluation of the correlations between the HSSI and the CI at various depths. It can be seen that as the soil measurement depth increased, the correlation between the HSSI and the CI increased, and that the overall gradient was close to 1. Our results are in

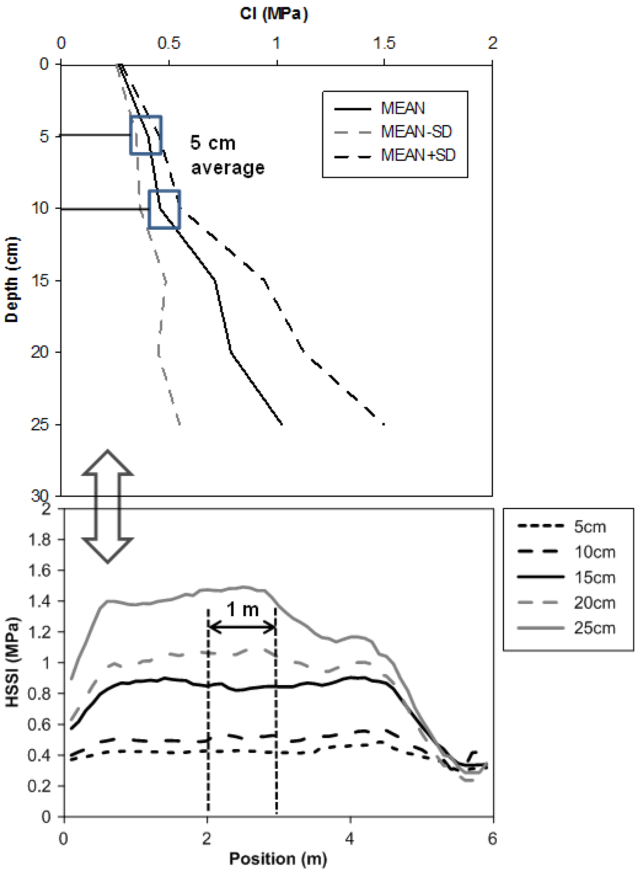

Figure 15. Typical CI measurements. For a reliable comparison of the measurements, 5 cm depth-averaged CIs and 1 m distance-averaged HSSIs were used.

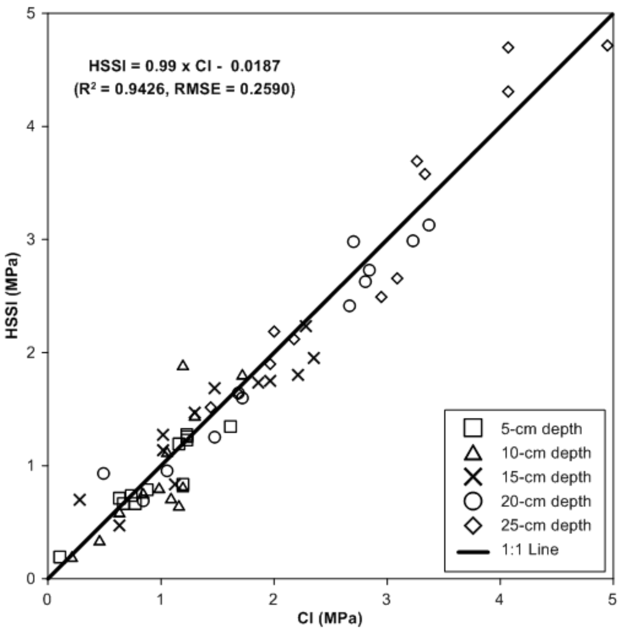

Figure 16. A continuous plot of the HSSI (20 Hz, 0.5 m/s), and a scatter plot of the CI at each depth (n = 12).

Table 3. Regression equation, coefficient, RMSE, and p-value at each depth using the soil bin test data

Depth (cm)	Regression equation	R^2	RMSE (MPa)	p-value
5	$HSSI_{05\ cm} = 0.82 \times CI_{05\ cm} + 0.12$	0.88	0.13	<.0001
10	$HSSI_{10\ cm} = 1.09 \times CI_{10\ cm} + 0.14$	0.67	0.33	0.0012
15	$HSSI_{15\ cm} = 0.74 \times CI_{15\ cm} + 0.34$	0.86	0.22	<.0001
20	$HSSI_{20\ cm} = 0.91 \times CI_{20\ cm} + 0.12$	0.95	0.21	<.0001
25	$HSSI_{25\ cm} = 1.04 \times CI_{25\ cm} + 0.08$	0.93	0.34	<.0001
All Depth	$HSSI_{all} = 0.99 \times CI_{all} - 0.02$	0.94	0.26	<.0001

contrast to those of Chung et al. (2006), who reported that R^2 was 0.60 as a linear regression of the PSSI as a function of the CI ($\alpha = 0.05$) when at an estimated 30 cm depth. This linear relationship between the PSSI and the CI, with a slope of approximately 0.6, was found for field data collected at a 30 cm depth. However, our result is similar to that of Hall and Raper (2005), who reported that R^2 was 0.97 and 0.98 as a linear regression of the WI as a function of the CI when used with the extended 625 mm^2 and 2500 mm^2 tips. This linear relationship between the WI and the CI was found with a slope of approximately 0.66 and 0.33 for the extended 625 mm^2 and 2500 mm^2 impedance sensing tips, respectively. The linear relationship between the HSSI and the CI was strongly correlated with a slope of 0.99, and an R^2 of 0.94 at all depths. If a field condition will be provided with similar texture, soil water content, and other soil properties as the soil bin, the developed sensor will be used instead of the CI measurement system. However, additional studies will be required to validate this relationship across a wide range of soil types from field tests. In addition, the potential effectiveness from application or fusion with other soil properties such as texture, water content, and electrical conductivity should be investigated using this developed RHSS.

Conclusions

Soil compaction that affects crops is known to be an element that enables the judgment of soil porosity and resistance to water infiltration or penetration and methods of measuring. This measurement method was standardized by the ASABE S313.4 standard and has since been commercialized as a method of vertically measuring a soil's resistance to penetration.

The present study related to the development of a real-time soil strength horizontal measurement system and a plowing depth control application system. However, before a plowing depth control system that applies to RHSS can be developed, an RHSS that can continuously measure soil strength needed to be developed. First, as design factors that are necessary for the development of a soil measurement system for horizontal soil strength, the size of the tips of the soil penetration resistance measurement sensors, spacing between sensors, and the materials of sensing tips and blades were selected. To verify the HSSI, which is measured using the RHSS divided by the cross-sectional area of the tip, the correlations between the CI and the HSSI were analyzed.

(1) Through review of existing case studies, and the cone penetration resistance profile of domestic soil, the maximum measurement depth was determined to be 50 cm, the measurement range to be at least 10 MPa, the tip penetration angle to be 30°, and the cross-sectional area of the base plane to be 254 mm^2. CI profiles were reviewed through statistical analysis to determine an appropriate number of tips, and spacing between tips; based on the results, the number of tips was determined to be 10, and tip spacing to be 5 cm. The selected load cell could be measured for a maximum soil horizontal penetration resistance value of 19 MPa and a resolution of 254 Pa. To reduce the amount of load applied in the direction of the progress of the soil horizontal penetration resistance measurement sensor tips, the starting cross-section of the tip support blades was designed to have a thickness of 18 mm, the same as the base width of the tips, and a cross-sectional soil penetration angle of 30°. A frame for installing the sensor-blade assembly on tractors was designed and fabricated.

(2) As for the shape and material of the penetration tips, the penetration tip cone diameter was chosen as 18 mm, and the penetration angle was specified as 30°. The tips were made in a size between 20.27 mm and 12.83 mm, which are the sizes presented in ASABE S313.3. The sensor tips were made of stainless steel. The blade was designed to have an angle of 30°, the same as the angle of the sensor tips, and was made of stainless steel. The stainless steel used here was STA301 series. In addition, the shaft of the sensor tips was made with a 16 mm diameter to minimize the frictional force that might occur on the shaft during the horizontal resistance measurement of the soil.

(3) The sensors were calibrated and significant linear relationships ($R^2 = 0.99$; $P < 0.0001$) were obtained. The basic operational performance of the RHSS was tested in an artificial soil bin at a moving speed of 0.5 m/s. As the number of processing times by the soil compacting roller increased, the degree of soil compaction increased, leading to increases in the HSSI. At a depth of 25 cm, the HSSI value was 0.3 MPa for one and three times of compacting roller processing, 0.8 MPa for seven roller operations (which is approximately three times higher compared with one and three times), and 1.3 MPa at nine times (which is approximately four times higher compared with one and three times. In the artificial soil bin, the HSSI and the CI showed linear relationships; the gradient was 0.99, the coefficient of determination was 0.94, and the RMSE was 0.2590.

Conflict of Interest

The authors have no conflicting financial or other interests.

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