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# Performance Test of a Real-Time Measurement System for Horizontal Soil Strength in the Field

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## Abstract

**Purpose:** Soil strength has been measured using a cone penetrometer, which is making it difficult to obtain the spatial data required for precision agriculture. Our objectives were to evaluate real-time horizontal soil strength (RHSS) to measure soil strength in real time while moving across the field. Using the RHSS data, the tillage depth was determined, and the power consumption of a tractor and rotavators were compared. **Methods:** The horizontal soil-strength index (HSSI) obtained by the RHSS was compared with the cone index (CI), which was measured using a cone penetrometer. Comparison analysis in accordance with the measurement depth that increased at 5-cm interval was conducted using kriged maps at six sensing depths. For tillage control and evaluation of the power consumption, the system was installed with a potentiometer for tillage depth, a torque sensor from the rear axle, and a power take-off (PTO) shaft. **Results:** The HSSI was lower than the CI, but they were the same at 54.81% of the total grids for the 5-cm depth and at 3.85% for the 10-cm depth. In accordance with the recommended tillage map, tillage operations between 0 and 15 cm left 2.3% and 7% residue cover on the soil, and that between 20 and 10 cm covered a wider utilization of 3% and 18.4%, respectively. When the tillage depth was 15 cm, the comparison result of the power requirements between the PTO and rear axle in terms of control performance revealed that the maximum power requirements of the axle and PTO were 44.63 and 23.24 kW, respectively. **Conclusions:** An HSSI measurement system was evaluated by comparison with the conventional soil strength measurement system (CI) and applied to a tractor to compare the tillage power consumption. Further study is needed on its application to various farm works using a tractor for precision agriculture.

**Keywords:** Cone index, Horizontal soil strength, Power consumption, Precision agriculture, Tillage control

## Introduction

Soil is one of the most important resources for crop growth and harvest and should be considered in agricultural machine design or management system. Soil tillage is essentially performed for agricultural production and management. However, plowing and harrowing works for soil tillage requires large amounts of input in terms of energy and labor.

Lee et al. (2011) investigated the engine power consumption of a tractor while operating the plow, rotavator, baler, and wrapper in South Korea. They reported that the power consumptions for each operation were 35.4, 48.5, 46.3, and 20.7 kW, respectively, and the rotavator consumed the largest amount of power (48.5 kW) during operations.

During the plowing work using the rotavator and plow, the soil strength and tractor speed affected the traction efficiency of the tractor (Park, 2009). In general, as the tillage depths and soil strength increase, the energy required for plowing also increases. In particular, if the tillage in the plowing work is performed on very deep soil, energy losses would be incurred due to the increase in the tractor traction power and tire slip. In contrast, if

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the tillage is performed on shallow soil, adequate work efficiency cannot be obtained owing to incomplete soil tillage. Therefore, hitch control systems should be used on a tractor according to variable soil conditions; thus, a tillage depth control can yield appropriate work efficiency. Only a few studies on a rotavator tillage depth control system based on real-time soil data are available. To realize energy savings during plowing, the tillage depths should be continuously controlled by measuring the soil strength in the field.

Researchers have developed a soil sensor and methods that can measure the soil strength, which are applied in various fields such as estimation of soil properties and mapping. To quantify the soil strength according to its depth and to obtain information related to the soil compaction and morphological characteristics, a cone penetrometer was developed (Mulqueen et al., 1977). The soil-strength index measured by a cone penetrometer, namely, cone index (CI, MPa), is defined as the force per unit base area required to push the penetrometer through a specified small increment of soil (ASABE, 2008). Jung et al. (2008) reported that soil compaction affects the root growth of soybeans at 1.1 MPa for clayey soil, 1.3 MPa for silty soil, and 1.6 MPa for sandy soil using the CI. Min et al. (1983) found that subsoiling requires different depths and spacing in clay-loam paddy soils to improve the soil physical properties for increasing rice yield. They also found that the maximum CI value was less than 1 MPa for depths ranging from 10 to 30 cm after performing subsoiling.

CI was utilized to predict the relationships between traction power and plowing resistance (Lee et al., 2009; Park, 2009; Park et al., 2012). To overcome the limits in terms of time, labor, and cost consumption in manual measurement, a digital soil CI measuring device was developed to replace the conventional analog-type device (Lee et al., 2010). To collect sufficient CI data from various field within a limited time, several on-the-go soil-strength sensor (OSSS) have been developed (Hall and Raper, 2005). The OSSS had a single sensor mounted on the leading edge of a shank while it horizontally passed through the soil. They used 30° prismatic wedge with 625-$mm^2$ flush-mounted, 625-$mm^2$ extended, and 2500-$mm^2$ impedance-sensing tips and defined wedge index 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 measures the soil strength up to a depth of 50 cm 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 with the CI (MPa) of the cone penetrometer. The PSSI data predict soil properties such as soil water content, bulk density, and texture (Chung et al., 2008). The best results are obtained when the depth information collected from the PSSI data is included in the model that relates the soil strength to the soil properties or when analysis is 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, collecting data for real-time applications is still needed such as in sensor network and direct decision making while operating in the field. Cho et al. (2015) developed a sensor for a measurement system called real-time horizontal soil strength (RHSS) system, which measures the soil strength on cone tips located at 50-cm depth with 5-cm increments. They defined the horizontal soil-strength index (HSSI, MPa) as the horizontal force measured by the RHSS divided by the base area of the cone tips, as compared with the CI (MPa) of a cone penetrometer on a soil bin. They reported the coefficient of determination ($r^2$ = 0.67 to 0.95) between the CI and HSSI measured at depths of from 5 to 25 cm.

The overall goal of the current research is to test the performance and application of the strength measurement using the RHSS system developed by Cho et al. (2015). The specific objectives of this study are as follows:

1. Examine the field test by comparing the CI and HSSI and determine the soil tillage depth using HSSI
2. Compare the determined depth and power consumption of the tractor and rotavators

## Materials and Methods

### Performance experiment using RHSS

Data were obtained from a field in North Chungcheong Province, South Korea. The area was 0.18 ha, and the soil classification was sandy loam composed of 42.3% sand, 32.6% silt, and 25.1% clay according to the USDA soil textures classes. The RHSS (Cho et al., 2015) system was equipped with 10 sensor tips with different depths for soil-strength measurement according to the depth, and

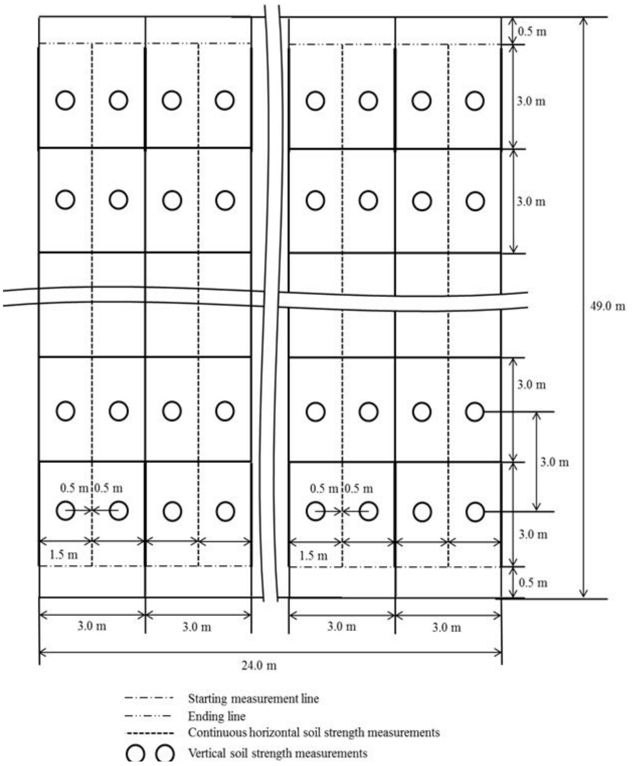


**Figure 1.** Experimental plot layout of the HSSI and CI field measurements.

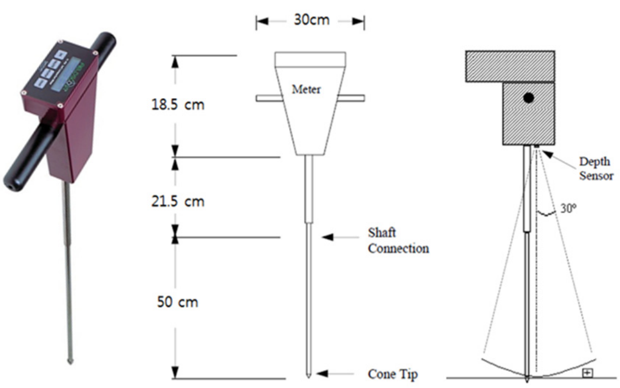


**Figure 2.** Photograph and measurement principles of the cone penetrometer.

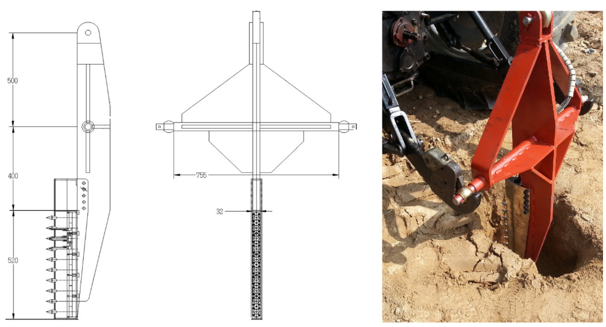

**Figure 3.** Drawing and photograph of the RHSS sensor attached to the tractor.

they could be attached to the tractor to measure on-the-go the horizontal penetration resistance in real time while the tractor travels on the field. The values were obtained by dividing the penetration resistance (force, N) measured at each tip of the RHSS sensor by the cross-sectional area (area, $m^2$) of each sensor tip, defined as the HSSI (MPa). Figure 1 shows the method of measuring the RHSS in the field. A width of 3 m was divided into two sections to measure the CI using a cone penetrometer (Figure 2) two times at an interval of 3 m. The CIs at both sides of the path were measured at intervals of 50 cm in a 49-m section, that is, 16 times per side and 32 times in one experiment. Then, the average of the two vertical penetration resistance values measured on the two sides was used. The RHSS were measured on the three-point hitch attached to the tractor (Figure 3). The tractor used in this experiment was TYM T993 (Dongyang, Iksan, Korea), which has 63 kW of rated engine power and 58.7 kW of rated power take-off (PTO) power (Table 1). The tractor speed during the RHSS measurement was 0.5 $m \cdot s^{-1}$.

## Measurement system for tillage control

Previous studies (Jung et al., 2008; Min et al., 1983) reported that the maximum CI for soybeans and rice on a paddy field is less than 1.0 MPa. The flowchart of the tillage control system is shown in Figure 4. From the block kriged maps of the HSSI data, the tillage depth was determined at the depth of the tips where the soil strength was measured. The determined tillage depths from the block kriged map were divided into blocks located by GPS. Depth control of the rotavator was performed according to the tillage depth recommendation. At this time, the soil depth location of the rotavator was calculated from the height of the three-point hitch. When the soil strength satisfied the condition of tillage control (e.g., HSSI > 1 MPa), the tillage control performed lifting or lowering of the rotavator according to the GPS location.

The tractor that controlled the rotavator was LS-PS100 (LS-mtron, Wanju, Korea), which has 70.8 kW of rated engine power and 61.9 kW of rated PTO power. It has a hitch-level control system that uses electro-hydraulic control (Table 1). The rotavator was G190 (Kyung-Il, Hwasung, Korea), which has a tillage width of 1.9 m. When the rotavator was operated, the transmission gear of the tractor was set to the low-2 level, and the PTO transmission level was set at level 2 (809 rpm). Experiments on the tillage depth control of the rotavator were performed using

**Table 1.** Tractor specifications for the measurement

| | TYM T993 | LS-PS100 |
|---|---|---|
| Length (m) × width (m) × height (m) | 4.1 × 2.2 × 2.7 | 4.1 × 2.0 × 2.6 |
| Weight (kg) | 3,685 | 4,080 |
| Rated engine power (kW) | 63.0 | 70.8 |
| Rated PTO power (kW) | 58.7 | 61.9 |
| PTO rotational speed (rpm) | 540, 747, and 988 | 634, 809, and 1082 |
| Transmission level | Main 8 and Sub 4 | Main 4 and Sub 3 |
| Tractor speed (m/s) | 0.1-10.2 | 0.4-10.0 |
| Photograph |  |  |

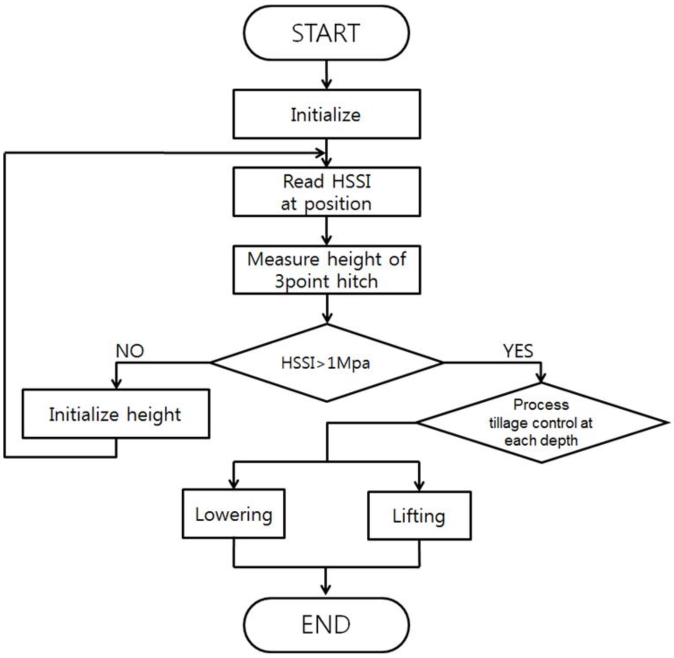


**Figure 4.** Algorithm of the tillage depth control system.

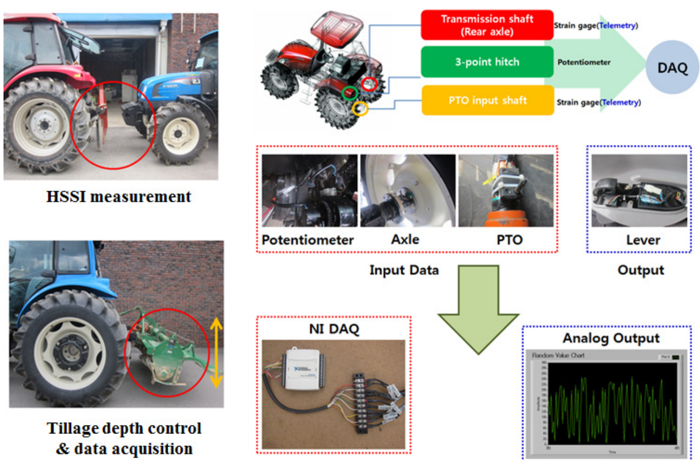


**Figure 5.** Schematic of the measurement and DAQ systems.

**Table 2.** Specifications of the strain gauge, telemetry system, and DAQ system

| Model | | Term | Value |
|---|---|---|---|
| Strain gauge (CEA-06-250US-350) | | Resistance (Ω) | 350 |
| | | Strain range (%) | ±5 |
| | | Resistance tolerance | ±0.4 |
| | | Operating temperature (°C) | -75 to 175 |
| Telemetry system (TorqueTrak 10K) | | Resolution (bits) | 14 |
| | | Sample transmission rate (Hz) | 2400 |
| | | RF transmission distance (m) | 6 |
| | | Signal-to-noise ratio (dB) | 67 |
| | | Signal delay (ms) | 4.2 |
| DAQ (NI-DAQ-6009) | Analog input (eight channels) | Resolution (bits) | 14 |
| | | Sampling rate ($kS{\cdot}s^{-1}$) | 48 |
| | | Voltage range at full scale, single-ended (V) | ±10 |
| | | Absolute accuracy at full scale, single-ended (mV) | 7.73 |
| | Analog output (two channels) | Resolution (bits) | 12 |
| | | Voltage range (V) | 0 – 5 |
| | | Absolute accuracy (mV) | 7 |

the same path as that followed in measuring the RHSS. For tillage control and evaluation of the power consumption, the system was installed using a potentiometer for tillage depth and a strain gauge from the rear axle and a PTO shaft (Figure 5). The potentiometer that detects the hitch height was STF3300 (Japan Resistor Mfg. Co., Hitoshi Kimura, Japan), which could measure from 0° to 60° with 5% accuracy. The power consumption was measured using a telemetry system on the PTO shaft and rear axle of the tractor wheel (Kim et al., 2011). The torques of the PTO and axle were measured using a four-element full-bridge strain gauge, namely, CEA06-250US-350 (VPG Co., Malvern, PA, USA). The data logger for the telemetry system was TorqueTrak 10K (Binsfeld Engineering Inc., Maple City, MI, USA). The specifications of the strain gauge and telemetry system are listed in Table 2. The sensors of the torque and telemetry system were calibrated by Jeonbuk Institute of Automotive Technology (Gunsan-si, Jeollabuk-do, South Korea). The power was calculated from the torques of the PTO and wheel axle (Eq. 1). The hitch height (potentiometer) and power (PTO and wheel) were collected by a data acquisition (DAQ) instrument, namely, NI-DAQ-6009 (National Instruments Co., Austin, TX, USA). This DAQ system has eight analog inputs with 14 bits and two static analog outputs with 12 bits and performed feedback for decision making from the sensor input (Table 2).

$$Power_{\,axle\ or\ PTO}\,(kW) = \frac{2\pi \times T \times N}{60{,}000} \quad (1)$$

where $T$ is the torque (N·m) and $N$ is the rotation speed (rpm).

## Results and Discussion

### Performance test of RHSS in the field

Figure 6 shows the scatter plots of the CI versus HSSI at different depths in the field performance tests. The scatter plots appear to have much more deviated from the 1:1 line than the results of the analysis of the HSSI-CI correlations ($r^2$ = 0.94) in the artificial soil bins conducted by Cho et al. (2015). These deviations are considered attributable to the more diverse environmental conditions than the controlled artificial experimental conditions. This correlation coefficient ($r^2$ = 0.14) is lower than that in the soil bin, and this is considered to be related to the lower accuracy of the individual relevant points when compared with the CI, rather than the low adaptability of the HSSIs. Thus, additional analysis techniques are considered necessary for this experiment.

Figure 7 shows the maps of the HSSIs and CIs measured in an area of 24 m by 49 m with the grid spacing set at 3 m interpolated using the kriging method. Sections where the HSSI values are 2 MPa or larger appear from a depth of

20 cm. When the value of the penetration resistance that can affect the crop roots is assumed to be 1 MPa, sections that require plowing exist from a depth of 10 cm. The maximum CI value exists between the depth of 25 and 30 cm. In addition, as the depth increases, the CI value increases, which is considered attributable to the natural subsidence of the soil. In the 5-cm-deep sections, most CI values are not more than 1 MPa. CI values that exceed 2 MPa appear at a depth of 10 cm or in deeper sections. HSSI values that exceed 2 MPa are found at a depth of 20 cm or in deeper sections. When compared with the CI maps, the HSSI maps measurements were relatively lower. From the comparison of the two grid maps, we can identify that the HSSIs show relatively lower soil strength distributions than the CIs. This result was also obtained by Cho et al. (2015), which could be understood as the characteristic of the horizontal strength measurement methods. In other words, as the measured depths decrease, the HSSIs show more similar measurement characteristics to those of the CI values. However, when the measured depths become deeper, the HSSIs display a characteristic of smaller measured soil-strength values than the CI. We can see that the HSSI distribution maps in the 15-20-cm deep sections show similar shapes to those of the CI values, and in the 25-30 cm deep sections, the distributions of the HSSI values are larger than the CI values in the distributions of the CI values. When the RHSS system is applied to the plowing process in cases where the target depth is not 10 cm, the CI values can be estimated based on the HSSI values. Table 3 lists the results of the analysis of the degree of correlation between the HSSIs and CIs in the field. According to the results listed in Table 3, the HSSIs and CIs coincide by 54.81% in the 5-cm-deep sections but coincide only by 3.85% in the 10-cm-deep sections. Most coincidental spatial data are formed in the 5-cm-deep sections.

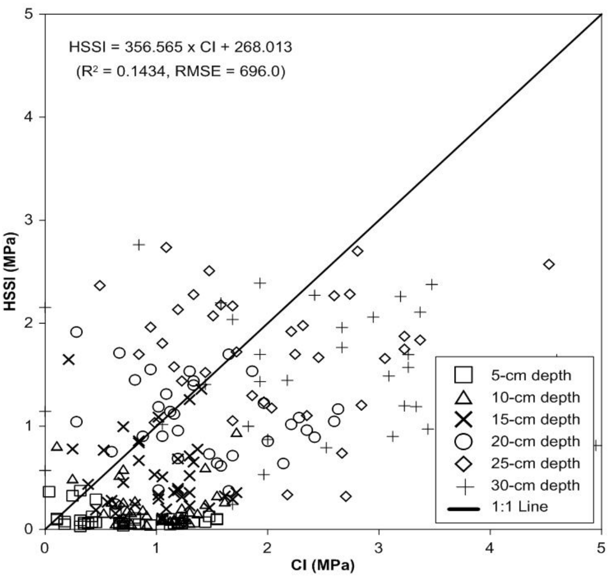


**Figure 6.** Scatter plots of the CI versus HSSI for different depths in the field performance tests.

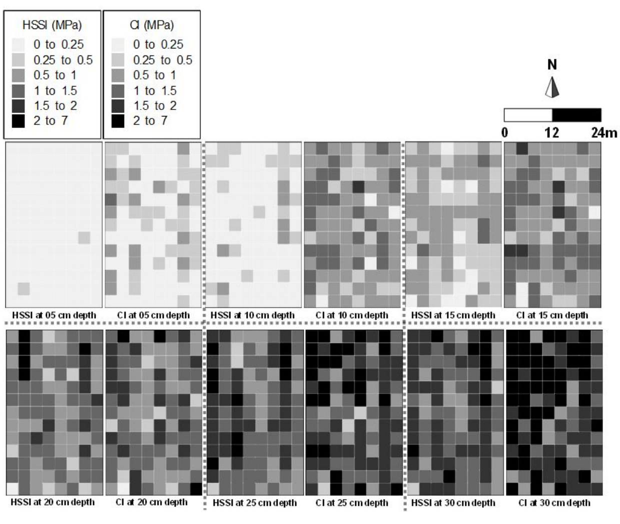


**Figure 7.** Comparison of the kriged maps of the HSSI and CI (3 m × 3 m grid) at six sensing depths.

## Tillage control using the HSSI data

Figure 8 shows the response of the tillage depth control system during the ascending and descending processes of the three-point hitch. The position at the beginning of the hitch was 6 cm in the ascending case and 9.3 cm in the descending case. During ascension, approximately 0.73 s (rise time) was taken to reach the target value of 9.3 cm. According to the potentiometer, the delay time was 0.33 s. After passing the maximum peak time, the time required to finally reach within the range of 5% from the target value and to be maintained was determined to be at a minimum of 3.73 s (setting time). During the descending process, 1.93 s (rise time) was taken to initially reach the target value of 6 cm. The delay time was 0.85 s, and the setting time was 5.20 s for the value to be within the 5% permissible range from the target value after passing the minimum peak time.

Figure 9(a) shows the tillage depth recommendation map based on spatial variability from the kriging method (3 m × 3 m). The tillage depth recommendations were determined based on 1.0 MPa resistance from the continuously measured horizontal soil strength (HSSI) data from the

**Table 3.** Pixel count and ratio to the total pixel showing the same levels of HSSI and CI

| Depth | | Range (HSSI and CI, MPa) | | | | | | Total (104) |
|---|---|---|---|---|---|---|---|---|
| | | 0.00 -0.25 | 0.25 -0.50 | 0.50 -1.00 | 1.00 -1.50 | 1.50 -2.00 | 2.00 -7.00 | |
| 5 cm | Pixel count | 56 | 1 | - | - | - | - | 57 |
| | Ratio to total pixel (%) | 53.85 | 0.96 | | | | | 54.81 |
| 10 cm | Pixel count | 2 | - | 2 | - | - | - | 4 |
| | Ratio to total pixel (%) | 1.93 | | 1.93 | | | | 3.85 |
| 15 cm | Pixel count | - | 2 | 25 | 1 | - | - | 28 |
| | Ratio to total pixel (%) | | 1.93 | 24.04 | 0.96 | | | 26.92 |
| 20 cm | Pixel count | - | - | 6 | 14 | - | 1 | 21 |
| | Ratio to total pixel (%) | | | 5.77 | 13.46 | | 0.96 | 20.19 |
| 25 cm | Pixel count | - | - | 1 | 13 | 14 | 4 | 32 |
| | Ratio to total pixel (%) | | | 0.96 | 12.5 | 13.46 | 3.85 | 30.77 |
| 30 cm | Pixel count | - | - | 2 | 6 | 11 | 5 | 24 |
| | Ratio to total pixel (%) | | | 1.93 | 5.77 | 10.58 | 4.81 | 23.08 |

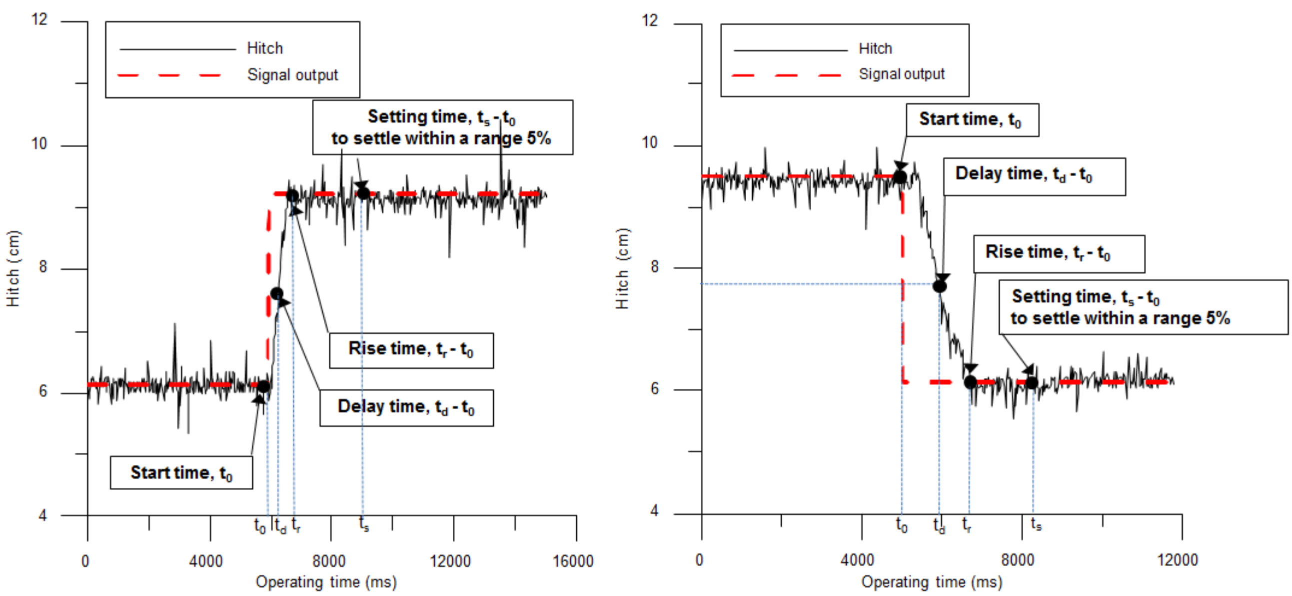


**Figure 8.** Response of the tillage depth control system during the (left) ascending and (right) descending processes of the three-point hitch with no soil.

experimental soil from previous studies (Jung et al., 2008; Min et al., 1983). On the basis of the hard pan layer thicknesses of 5-25 cm that affect the root growth and strength at 1.0 MPa, the tillage depths by section of the five parts divided at intervals of 5 cm were determined. The area where tillage depth control was unnecessary was at the tillage depths of 5-20 cm, which was 12.40% of the entire area. The areas where tillage depth control was necessary were at tillage depths of 15 and 20 cm, which were determined to be 28.7% and 12.4%, respectively, of the entire area.

Figure 9(b) shows the tillage performance evaluation maps from the kriging method (3 m × 3 m). These maps show the actual plowed depths in the field experiments, which reflect the settling and delay times that represent the measures of the control stability. At depths of 0-5 cm and 15 cm, 2.3% and 7% of the area, respectively, was not plowed, whereas at depths 20 and 10 cm, 3% and 18.4% of the area, respectively, were unnecessarily overplowed.

Figure 10 shows the hitch movement power consumption when the tillage depth was controlled. The target depth should be controlled according to the tillage depth

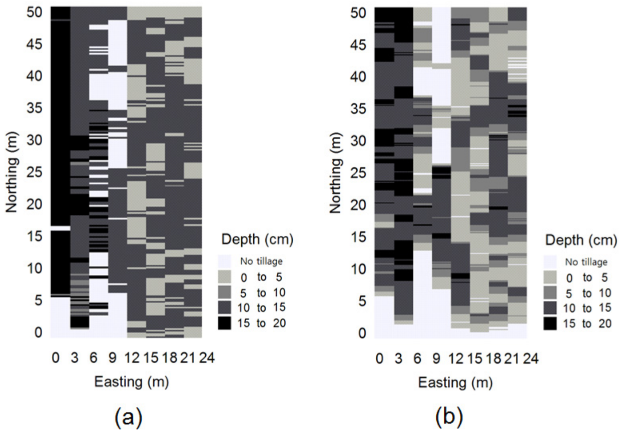


**Figure 9.** (a) Tillage depth recommendation map based on spatial variability and (b) tillage performance evaluation map.

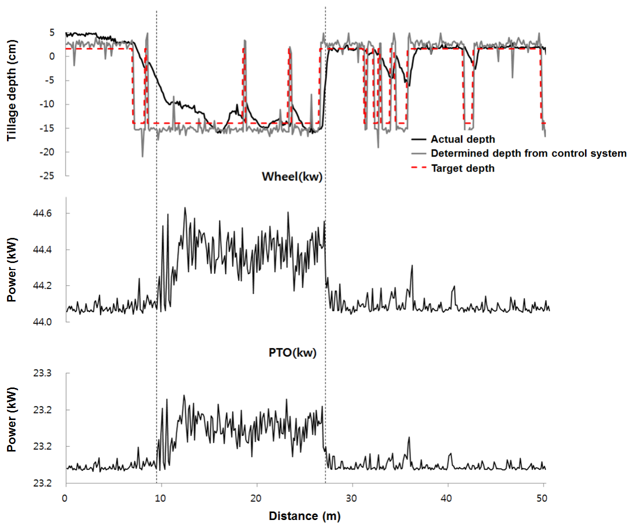


**Figure 10.** Hitch movement and power consumption of the tillage depth control.

recommendation map. When the target depth was applied to the depth control system, the value determined by the control system could contain an additional noise signal such as engine vibration and the up and down motion of the self-loading rotavator. In addition, the actual tillage depth could also be varied by the response time of the tillage depth control, field conditions, and tractor and rotavator loads. During the descending process from a distance of 8 to 16 m, the target depth rapidly increased at a distance of approximately 9 m, but the actual depths were slightly reduced. This figure shows the tillage depths and the power consumption trends of the PTO and the axle during actual plowing. The PTO and the axle power consumption gradually increased from the point where the tillage depth control began, and the largest power was consumed in the 9-27-m section. When plowing at a tillage depth of 15 cm, the maximum axle and PTO power consumption values were determined to be 44.63 and 23.24 kW, respectively. From the aforementioned results, an appropriate tillage depth control is considered to be capable of reducing the power consumption of the axle and the PTO input axis.

## Conclusions

The present study is on the RHSS developed by Cho et al. (2015), which we investigated in a field test by comparing the CI and HSSI results with its implementation. In addition, this study was carried out to develop an efficient tillage depth control system of a tractor based on soil compaction in the field. A tillage recommendation map was proposed that continuously acquire soil hardness data using a horizontal soil-strength measurement system. On the basis of the soil hardness data, the tillage depth was controlled, and the control performance was evaluated. The tillage depth control system can determine the optimum tillage depth for a specific point. The results of this study are summarized as follows:

(1) The field tests showed linear relationships between the HSSI and CI results, but the statistical significance was lower than the results obtained from the soil bin tests. The kriged HSSI maps showed a basis on the spatial variability according to the depth. It presents relatively low variability at depths of 15-25 cm and high variability at depths of 5-10 cm, indicating that a real-time tillage depth control using spatial field location is more effective at shallow depths. In general, the HSSI is lower than the CI, but they are the same at 54.81% of the total grid at the 5-cm depth and 3.85% of the total grid at the 10-cm depth.

(2) The response of the tillage depth control took a delay time of 0.47 s and a settling time of 5.34 s when the rotavator ascended. In addition, the delay time was 0.85 s and the settling time was 5.34 s when the rotavator descended.

(3) According to the recommended tillage map, tillage operations between 0 and 15 cm left a residue cover of 2.3% and 7% on the soil, respectively. However, different sections between 20 and 10 cm were more widely used at 3% and 18.4%, respectively.

## Acknowledgment

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## Conflict of Interest

The authors have no conflicting financial or other interests.

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