바이오시스템공학 (*J. of Biosystems Eng.*)
Vol. 33, No. 5, pp. 355~361 (2008. 10)

이동식 토양 강도 센서 데이터 주파수 분석

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Spectral Analysis of On-the-go Soil Strength Sensor Data

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Abstract

As agricultural machinery has become larger and tillage practices have changed in recent decades, compaction as a result of wheel traffic and tillage has caused increasing concern. If strategies to manage compaction, such as deep tillage, could be applied only where needed, economic and environmental benefits would result. For such site-specific compaction management to occur, compacted areas within fields must be efficiently sensed and mapped. We previously developed an on-the-go soil strength profile sensor (SSPS) for this purpose. The SSPS measures within-field variability in soil strength at five soil depths up to 50 cm. Determining the variability structure of SSPS data is needed for site-specific field management since the variability structure determines the required intensity of data collection and is related to the delineation of compaction management zones. In this paper, soil bin data were analyzed by a spectral analysis technique to determine the variability structure of the SSPS data, and to investigate causes and implications of this variability. In the soil bin, we observed a repeating pattern due to soil fracture with an approximate 12- to 19-cm period, especially at the 10-cm depth, possibly due to cyclic development of soil fracture on this interval. These findings will facilitate interpretation of soil strength data and enhance application of the SSPS.

Keywords : Soil sensor, Soil strength, Compaction, Variability, Spectral analysis

1. INTRODUCTION

Site-specific management (SSM) has been studied and increasingly adopted in many countries throughout the world. Soil properties are some of the most important information sources for SSM because soil physical and chemical properties govern the transport of nutrients and water in the soil and the amount of plant available nutrients and water (Barber, 1984). Compaction, a soil physical property, is a concern in crop production and environmental pollution. Soil compaction often restricts root development and growth (Lipiec and Stepniewski, 1995) due to increased bulk density and/or strength of the soil (Guerif, 1994), reduces the biological activity of plant roots and organisms in the soil due to reduced aeration (Voorhees et al., 1975), and limits water infiltration. The causes of soil compaction and the resulting soil deformations may be different in the various soil layers (i.e., top layer, arable layer, and subsoil) (Koolen and Kuipers, 1983). Therefore, quantifying spatial and vertical variability in soil compaction and related soil properties would be useful in SSM.

An approach to estimate the state and variability of soil compaction is to measure soil strength, since soil strength is strongly associated with compactness, packing density, relative

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The article was submitted for publication on 2008-08-19, reviewed on 2008-09-05, and approved for publication by editorial board of KSAM on 2008-09-22. The authors are Sun-Ok Chung, Full Time Instructor, Chungnam National University, Daejeon, Korea, Kenneth A. Sudduth, Agricultural Engineer, USDA-ARS Cropping Systems and Water Quality Research Unit, and Jinglu Tan, Professor, Biological Engineering Department, University of Missouri, Columbia, Missouri, USA. Corresponding author: K. A. Sudduth, USDA-ARS Cropping Systems and Water Quality Research Unit, 269, Agricultural Engineering Building, University of Missouri, Columbia, MO, 65211, USA; E-mail: <ken.sudduth@ars.usda.gov>.

bulk density, and drainable porosity (Canarache, 1991). The cone penetrometer has been the major tool used to quantify soil strength in-situ (e.g., Mulqueen et al., 1977). A cone penetrometer, however, operates with a "stop-and-go" procedure and collects data only at discrete locations, making it difficult to collect the amount of data required to detect statistically significant differences in the soil strength profile among treatments or locations. Generally, this problem has been addressed by obtaining a large number of measurements, a process that is time-consuming and labor-intensive.

A number of researchers have attempted continuous measurement of soil strength at multiple depths (e.g., Glancey et al., 1989; Adamchuk et al., 2001; Chukwu and Bowers, 2005; Hall and Raper, 2005; Chung et al., 2006; Andrade-Sanchez et al., 2007). These on-the-go soil strength sensors have differed in (1) the type of soil strength measured, (2) number of sensing elements, and (3) the shape and extension of sensing tips. Although these prototype sensors have been able to provide on-the-go soil strength data, they are all still in development and testing stages. For better application of the sensors and their measurements, it is important to understand variability of the sensor signals and to investigate the factors that may affect this variability.

Spectral Analysis

Spectral (or frequency) analysis is the process of obtaining the frequency content of a signal (spectrum) using basic mathematical tools (Proakis and Manolakis, 1996). Thus, spectral analysis can be used to decompose a signal into frequency components. When applied to soil strength data collected over a temporal or spatial period (e.g., Lui et al., 1996), the frequency components can identify repeating spatial patterns of soil strength.

Researchers have utilized spectral analysis techniques to investigate the repeating pattern of tillage forces exerted by periodic loading and failure of soil blocks. Young et al. (1984) studied the force on a triangular-shaped vertical chisel operating at a nominal 0.9 m s^{-1} at three depths: 50, 100 and 150 mm. The tests were carried out in a Norfolk sandy loam soil with two compaction levels: a loose condition and a packed condition. A sampling rate of 100 Hz was used, corresponding to one sample every 9 mm of travel. Each run consisted of 1,024 samples of the draft force. To arrive at a stable estimate of the power spectral density (PSD), each run was divided into 16 subsections, each subsection consisting of 64 consecutive draft measurements. At a given depth, the PSD functions were similar in shape but differed in amplitude. The peak of the PSD was affected by compaction level. No significant responses were found at frequencies above 10 Hz, and the major frequency was about 2 Hz. The authors concluded that the predominant cyclic variation of the draft force was not random and that the predominant frequency corresponded to the rate of shear plane development.

Summers et al. (1985) presented a frequency analysis of forces on four tillage tools: moldboard plow, chisel plow, disk, and sweep plow. Draft force was collected at a frequency of 2,558 Hz for 1.4 s. The results showed that the draft and vertical force resulting from tillage tool-soil interaction appeared to be deterministic at frequencies of 1.43 Hz and 9.99 Hz with a superimposed random component.

Upadhyaya et al. (1987) analyzed the frequency of soil-tool force variation. A vertical blade was operated at a depth of 50 mm with two tool speeds: 0.22 m s^{-1} and 1.11 m s^{-1}. Soils used were (1) an artificial soil consisting of a solid phase of Gooselake fire clay and a liquid phase of 12.2% SAE 5W mineral oil, and (2) an artificial soil consisting of a solid phase of 50% Ball clay and 50% Ottawa silica sand and a liquid phase of 17% SAE 140 gear lubricant. From 130 to 216 recorded points were obtained from a frame-by-frame analysis of high-speed movies. The results indicated that the dominant frequency corresponded to the soil-fracture mode. It was also stated that the failure pattern and fracture distance might depend on soil type and condition (bulk density and water content), and tillage tool speed.

Objectives

The overall objective of this research was to investigate the variability structure of the soil strength data obtained with our previously developed soil strength profile sensor (SSPS). Specific objectives were to:

- Apply spectral analysis to soil bin data to investigate the effects of compaction level and operating speed on the variability of soil strength, and
- Investigate causes and implications of the variability.

2. MATERIALS AND METHODS

A. Soil Strength Profile Sensor

The SSPS (Fig. 1), configured with five prismatic force-sensing tips on a 10-cm depth increment and extended 5.1 cm ahead of a main blade, provided a soil strength profile to a depth of 50 cm (Chung et al., 2006). The sensing tips had a 60° cutting or apex angle and a base area of 361 mm^2, comparable to the base area of the ASAE-standard large cone penetrometer (ASABE Standards, 2005). Similarly to the penetrometer cone index (CI), force divided by the base area of the sensing tip of the SSPS was defined as a prismatic soil strength index (PSSI, MPa).

The soil force on each tip was measured by a load cell located in the main blade and in contact with the rear surface of the tip shaft. The signal from each load cell was sent to a data acquisition system (DaqBook/100[1]), Iotech Inc., Cleveland, Ohio) through a transducer amplifier (Model S7DC, RDP Electrosense Inc., Pottstown, Pa.). The amplifier provided low-pass filtering with a 20-Hz cutoff frequency.

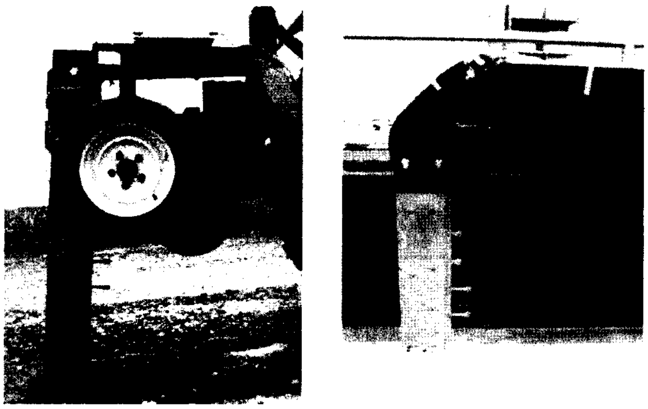

Fig. 1 Side view of the tractor-mounted SSPS raised out of the ground (left), and the SSPS blade mounted on a soil bin test cart (right).

B. Data Collection

Two types of PSSI data were obtained -- laboratory data for sensor (or load cell) calibration and soil bin data. For sensor calibration, a cylindrical laboratory test fixture was fabricated, and load cell output signal was sampled at 100 Hz for 20 s at six different loadings. Initially a cylindrical metal plate was put on top of the load cells and the zero-offset of the data acquisition system was adjusted. Then, five tractor weights were loaded and unloaded one by one. Forces applied by the weights were 0, 0.32, 0.66, 0.99, 1.32, and 1.64 kN. A detailed description of laboratory calibration was given by Chung et al. (2006).

Soil bin data were collected at the Deere and Company Soil Dynamics Laboratory (Moline, Ill.) at two compaction levels (high and low), three operating speeds (0.5, 1.5, and 2.5 $m\ s^{-1}$), and three depths (10, 20, and 30 cm), at a 100-Hz sampling frequency. The soil bin was 33 m long (14 m of soil) by 1.6 m wide and 0.85 m deep. The soil in the bin was 15% clay, 35% silt, and 50% sand, and soil water content was held constant to within 1% (i.e., 8.4 to 8.8%). Different levels of compaction could be achieved by adjusting the pressure of a compaction roller. With the low and high roller pressure settings, the nominal CI values near the soil surface were 0.55 and 0.99 MPa, respectively, and these levels were reasonably constant along the length of the soil bin. However, CI varied considerably with depth (mean CV = 25%), and also was slightly different between soil preparations. To reduce the number of soil preparations, two sensor passes and two compaction levels were implemented with each preparation.

Figure 2 shows examples of signals from the calibration (top) and soil bin (bottom) tests. The output signal for the calibration tests with static loading (Fig. 2, top) showed a normal distribution with a Kolmogorov-Smirnov statistic of 0.164 ($n=1995$, $\alpha<0.01$). Similar results were obtained for the other load cell-amplifier combinations. In soil bin tests, PSSIs were generally higher at greater depths and higher compaction levels.

C. Data Analysis

Spectral analysis was applied to the signals from load cell calibration and PSSI data collected in the soil bin. Before analysis, the mean signal level was subtracted from each data set to minimize the DC (0 Hz) component. For the soil bin data, the signal was trimmed to eliminate transitional

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1) Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by Chungnam National University, Korea, USDA-ARS, or the University of Missouri, USA

areas near the beginning and end of each pass, and around the transition from the low compaction to high compaction ("valid signal" in Fig. 2, bottom). Spectral analysis was conducted and averaged PSSI value for each run was calculated using the valid signal. The power spectral density (PSD), expressed as magnitude and dB (10 $\log_{10}$ (magnitude)), was estimated using the Welch's periodogram averaging method. This method reduces the variance of the power spectrum by dividing the original signal into segments and averaging the spectra of the segments. The spectral analysis was carried out with the "pwelch" function in MATLAB version 6.1 (The Math Works Inc., Natick, Mass.). Signals were divided into segments of 200 points with 50% overlap and windowed with a Hamming window for a resolution of 0.5 Hz. For each speed and depth, 6 or 8 PSD plots depending on the number of runs and additional PSD plot for combined all data from the runs were calculated. The PSDs were visually examined and relatively clear local peaks were selected as the dominant frequency components of the signal.

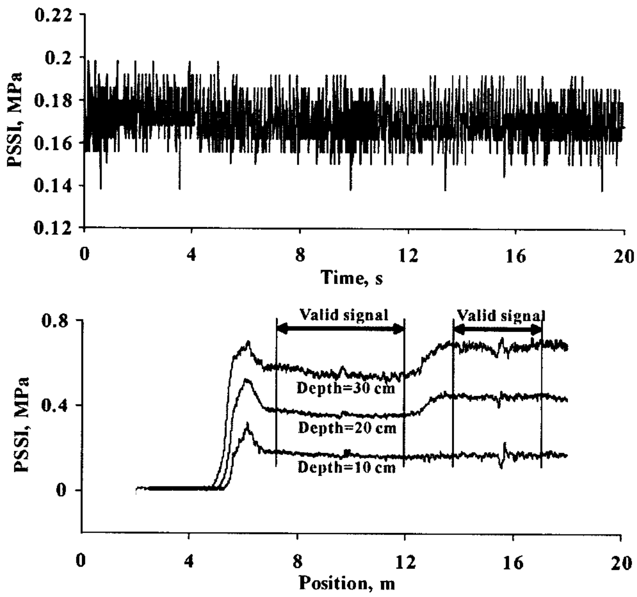

Fig. 2 Examples of signals from the calibration (top) and soil bin (bottom) tests.

3. RESULTS AND DISCUSSION

A. Laboratory Static Loading

Time series plots of the output signal for static loading showed that the load cells and data acquisition system were capable of recording reliable, low-noise signals (Fig. 2, top). The means of the PSSI ranges and standard deviations were 0.065±0.0002 MPa (95% confidence interval; Chung et al., 2006). PSD plots of these data (Fig. 3), however, consistently showed local peaks at 7.5 Hz (fundamental frequency) and 15 Hz (the second harmonic). The PSD levels of the peaks were slightly lower for signals with no loading than for those with loadings, but the levels were similar among the different loading levels. The static loading PSD peaks may originate from the data acquisition system (e.g., A/D conversion or data saving interval), therefore those peaks should be treated carefully in interpretation of PSD plots of the soil bin data. Although it would be preferable to have no PSD peaks under static loading conditions, these levels were considered negligible, considering the low PSSI values and standard deviations.

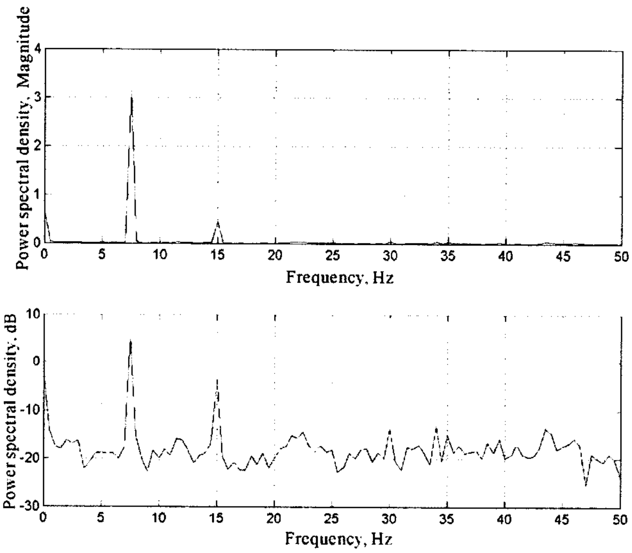

Fig. 3 An example PSD for static loading tests, with vertical axis scaled in linear (top) and dB (bottom) units.

B. Effects of Operating Speed and Depth (Soil Bin Data)

The PSD plots of the soil bin signal generally consisted of major peaks and small peaks between the major peaks (Fig. 4). Excluding the peaks at frequencies close to zero (1/f noise) and greater than 20 Hz (the cut-off frequency of the analog filter in the data acquisition system), from 0 to 3 major peaks were observed for each PSD plot, as summarized in table 1.

PSD peaks occurred at higher frequencies at greater operating speeds. These frequencies ranged from 2 to 4 Hz, 4 to 13.5 Hz, and 3 to 14 Hz at speeds of 0.5, 1.5, and 2.5 m s^{-1}, respectively (Table 1). The approximate frequency (3 Hz) of the peaks at 0.5 m s^{-1} corresponded to a distance of about 17 cm. At 1.5 m s^{-1}, the major frequencies were approximately 5, 8, and 13 Hz, corresponding to 30, 19, and 12 cm, respectively. At 2.5 m s^{-1}, the approximate frequencies were 5, 9, and 13.5 Hz, corresponding to 50, 28, and 19 cm, respectively. In many cases when multiple PSD peaks were observed, the higher frequencies were close to a multiplication of the smallest peak frequency (i.e., fundamental frequency). The smaller peak frequency (a repeating pattern on a longer distance interval) might be due to superimposition of the greater peak frequencies (a repeating pattern on a shorter distance). With this consideration, we attributed the dominant frequency to cyclic development of soil fracture on an interval of 12 to 19 cm. Video recordings of the soil bin tests showed this type and approximate scale of cyclic soil fracture pattern on the soil surface in front of the SSPS

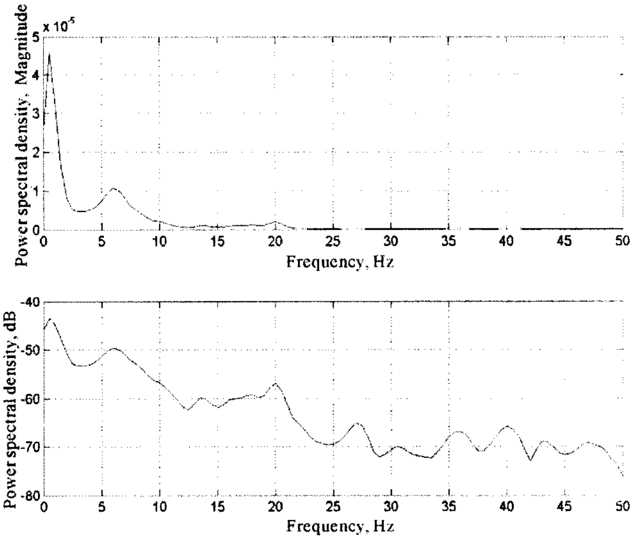

Fig. 4 An example PSD for the soil bin tests, with the vertical axis scaled in linear (top) and dB (bottom) units.

Table 1 Power spectrum peaks (> -70 dB; < 20 Hz) observed in soil bin tests

Speed (m s^{-1})	Depth = 10 cm		Depth = 20 cm		Depth = 30 cm	
	PSSI	Peak, Hz	PSSI	Peak	PSSI	Peak
0.5	0.134	3(-38.5)[1]	0.296	2.5(-48.9)	0.458	2(-44.2)
	0.139	2.5(-42.0)	0.315	-	0.507	-
	0.143	-	0.350	3(-41.3)	0.554	-
	0.148	2(-39.7)	0.360	-	0.600	-
	0.168	4(-51.6)	0.385	2.5(-44.0)	0.642	-
	0.170	-	0.448	3(-47.6)	0.685	-
	All	2.5(-43.6)	All	2.5(-46.5)	All	-
1.5	0.159	-	0.294	-	0.454	6(-50.4)
	0.161	8.5(-56.7), 12(-57.2)	0.308	7(-60.2)	0.474	5(-49.0), 13.5(-53.7)
	0.164	6(-60.4)	0.333	-	0.520	12(-54.3)
	0.169	4(-43.5), 9(-47.4)	0.381	-	0.655	-
	0.181	-	0.394	4(-53.4)	0.655	-
	0.182	-	0.440	4(-47.4), 9.5(-54.5)	0.725	13(-51.1)
	All	4.5(-52.2)	All	4.5(-50.0)	All	3.5(-45.6)
2.5	0.171	3.5(-56.0), 9(-59.2), 16(-58.2)	0.298	-	0.493	-
	0.187	5.5(-52.7), 14(-55.3)	0.335	-	0.545	7.5(-48.4), 13.5(-51.2)
	0.196	3(-50.8), 8(-53.1), 13(-53.9)	0.349	-	0.556	
	0.199	6(-54.2)	0.357	-	0.587	-
	0.207	4.5(-49.1)	0.418	-	0.682	-
	0.226	5.5(-47.4), 10(-52.2)	0.428	7.5(-53.4)	0.698	7.5(-46.5)
	0.226	5(-46.8)	0.451	8(-54.5)	0.714	-
	0.235	6(-49.7)	0.452	-	0.762	-
	All	5(-47.9), 14(-52.6)	All	3.5(-50.5), 8.5(-54.4), 13(-56.0)	All	-

[1] Numbers in parentheses are power spectral peaks in dB.

blade.

PSD peaks were found more consistently at the shallow depth (i.e., 10 cm) than at the deepest depth (i.e., 30 cm). This might indicate a more consistent development of soil fracture at shallower depths. Based on classical soil failure theory, Godwin and Spoor (1977) identified two failure mechanisms with narrow tines; crescent failure occurring near the ground surface, where soil displacement had forward, sideways and upward components, and lateral failure deeper in the profile, where soil displacement had only forward and sideways components. They showed that a flat vertical tine of 2.5-cm width (the same width as the main blade of the SSPS), lateral failure occurred at depths greater than about 12 cm. When the maximum depth of crescent failure was 12 cm, calculated forward distances of soil rupture with a flat tine were 17 and 72 cm for completely cohesive and frictional soils, respectively. This range of rupture distances encompassed the range of PSSI frequencies found in the soil bin tests, providing further evidence that these peak frequencies were likely due to the cyclic development of soil fracture.

4. CONCLUSIONS

The variability structure of soil strength (PSSI) measured with our previously developed soil strength profile sensor (SSPS) was investigated using spectral analysis techniques. The major findings were:

- In static loading tests for SPSS calibration, load cell signals were stable and low in noise level. Spectral analysis detected peaks at 7.5 and 15 Hz, possibly due to data acquisition characteristics, but they were considered negligible.
- Spectral analysis of soil bin data showed 0 to 3 major peaks. The dominant frequency was attributed to cyclic development of soil fracture with an interval of 12 to 19 cm. Frequencies where PSD peaks occurred were greater at greater operating speeds, and were more consistent at the shallow depth (i.e., 10 cm) than at the deepest depth (i.e., 30 cm), a possible indication of crescent soil failure at the shallow depth.

ACKNOWLEDGEMENTS

This research was part of an international joint project, “Development of Site-specific Optimum Soil Management Strategies and In-situ Soil Physical and Chemical Property Sensors for Realization of Environment-friendly Precision Agriculture”, between the Rural Development Administration, Republic of Korea and USDA-ARS, USA.

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