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Original scientific paper

Simple Method for Measuring and Mapping of Site-Specific Draft Force during Plowing

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Abstract: This paper presents and analyzes the procedure for indirect measurement of soil mechanical properties using strain transducers installed on the lower links of the tractor and corresponding acquisition equipment, along with simultaneous use of the tractor unit positioning equipment in the field during tillage operation with a two-furrow plough. Sensors are installed and calibrated according to measurement requirements and after the Finite Element Method (FEM) analysis of the tractor lower links. The results obtained for the draft force longitudinal measurements are well consistent with expected results predicted by using the Goryachkin approach and ASAE Standard D497.4. The presented method can be successfully applied to measure the draft force when performing any other operation in the field. Maps produced by measuring the draft force are very useful in precision seeding in terms of varying seeding depth or soil amelioration. Such maps can be a useful layer in any other decision-making considerations in precision agriculture.

Keywords: draft force; lower links; plowing; strain transducer

1 INTRODUCTION

In compact soils water and nutrient absorption by the plant is possible only up to a certain limit. Another consequence of soil compaction is reduced air exchange in the soil as well as reduced mineralization. Compact soil makes it difficult for root system and plant itself to develop. Due to compaction, the root cannot grow and is incapable to transport water and nutrients. This can reduce yields by 50%. Knowledge of soil structure is a key factor for proper and accurate decision-making in precision agriculture.

A large number of systems have been developed to indirectly assess soil physical condition by measuring soil mechanical resistance. The on-the-go systems include horizontal penetrometers with one or more than one measuring elements, vertical resistance measuring systems, and draft force measuring systems. In cases when soil mechanical properties are measured indirectly through the pulling force, this can be done using measuring frames or instrumentalized lifting mechanism. Plowing is the most rewarding operation during which measurements of this type can be made. During operation, the three-point linkage transfers forces acting on the implement to the tractor. Plowing is a highly power demanding soil tillage operation [1], comprehending cutting and turning up and over the surface soil layer enriched with minerals and decomposed organic matter, usually in the depth range of 15 - 30 cm. Going deeper increases the soil resistance and consumed energy. Beside the plowing depth, soil reactions toward plough depend on the plough design, mechanical and other soil physical parameters and the tractor speed [2]. There are several ways to measure pulling force more precisely, some of them are described in the cited works, however, most of them require more complicated preparation, measurement and more expensive equipment. In addition, the goal of this work is not to measure the traction force with absolute precision, but rather to observe its changes during the plowing process.

The paper presents a simple method for measuring the variability of pulling force. Pulling force i.e. draft force suggests soil compaction as an important parameter for agricultural production. The measurement is performed by instrumenting the tractor and during the plowing process using a two-furrow plough. The method can be applied to any other agricultural operation that is undertaken for the purpose of production and not primarily measurement. The procedure was carried out experimentally when plowing the experimental field immediately after the barley harvest, the plowing depth being 20 cm.

Research of the procedure for measuring and mapping the draft force involved considerations of different factors that affect this draft during tillage. The considerations were the basis for assumptions that define tillage conditions and performance of experiment in the experimental field.

Tillage depth was constant and amounted to 20 cm. The working load of the agricultural tractor depends on the soil resistance caused by the soil tool interaction during tillage operation. This means that the soil property distribution according to the soil layer and tillage depth [3-5] are the fundamental key factors that have the greatest influence on the working performance and mechanical load of agricultural tractors. The results indicated that increasing the tillage depth and/or the forward speed increased the draft, unit draft and vertical specific draft. Also, increasing the tillage depth increased the horizontal specific draft and the coefficient of pull, while increasing the speed decreased the horizontal specific draft and the coefficient of pull. About 16.6% of the draft force was directed towards cutting the soil and 83.4% was consumed in pulverization of soil particles [6].

Tillage speed was constant and amounted to 8 km/h. Al-Suhaibani and Ghaly [7] refer to the fact that the increase in the draft observed, when the forward speed was increased from 1,20 - 1,75 m/s, was lower than the increase in the draft observed when the forward speed was increased from 1,75 - 2,30 m/s. This may indicate that the forward speed of 1,75 m/s is the optimum speed. Hunt [8] reports that the draft force of a mouldboard plough is larger by 150% at the speed of 20 km/h than at the speed of 5 km/h. Research conducted by Eidet [9] shows that the dependence of the plough draft on the working speed is not universal for all types of mouldboards.

Soil moisture was uniform across the entire plot. Inchebron et al. [10] measured and analyzed tractor pull performances on clay soil in the soil moisture ranges of 16 - 18%, 19 - 22% and 23 - 25%. They revealed that rolling resistance and wheel slip increase and pull efficiency decreases as soil moisture increases. Rashidi et al. [11] assessed the effects of moisture content on mouldboard plough draft force and reported that traction decreased with increasing soil moisture content. The films of moisture surrounding the soil particles have a lubricating effect and soil strength decreases with increasing soil moisture content. Thus, dry soils have much stronger draft forces than wet soils and require relatively greater plowing forces. However, in this study soil moisture content range was narrow (16,1 - 25,4%) and only 32 soil samples were tested. Collins and Fowler [12] measured the traction on field test sites with four different soil characteristics. The soil moisture content in their field test sites was in the range of 12,0 - 30,0% and traction performance was highest for the field with 30,0 % moisture content.

Plowing conditions were ideal. There was no slip. Knowing the importance of wheel slip, several attempts have been made to measure this parameter. Researchers have used different techniques like microwave radar device [13-18] and electronic circuits using a photo-transducer (Zoerb and Popoff, 1967; Lyne and Meiring, 1977; Clark and Gillespie, 1979; Jurek and Newendorp, 1983; Grevis-James et al., 1981; Erickson et al., 1982; Shropshire et al., 1983; Musonda et al., 1983) [19-26] for accurate measurement of slip. Most of these techniques were tractor specific, costly and of unproven reliability for instantaneous measurement of slip. These techniques were based on calculation of theoretical velocity on test bed instead of operating on a hard surface which is essential for defining zero condition.

The plough is adjusted not to affect change in the pulling force. Reduction of the required power in tillage operation is possible to achieve by improving tractor adhesion to the soil, which is realized by adjusting the plough unit [27]. Research shows that 20 - 55% of available wheel tractor energy is lost in the wheel-soil contact [17]. Therefore, it is essential to investigate influencing factors through which it is possible to promote tractor pull properties, and thereby the efficiency level of the wheel tractor. The tractor pull efficiency is affected by multiple factors such as the soil type and condition, loading mass and distribution, construction and pressure in the tyres, eccentric and inclined pull, etc. [28-30].

The aim of this research is not to determine accurate values of the plough draft force. For meaningful and effective mapping of soil structure variability, it is sufficient to enable measuring of the soil mechanical resistance relative variability in contact with a plough during tillage, or in contact with any other working machine in additional soil tillage. Values of the plough draft forces are at a higher level and in a larger range compared to the value and range levels of pulling forces for other working operations and machines in the domain of soil additional tillage, therefore change in this pulling force during plowing is easier to see and easier to measure.

2 MATERIAL AND METHODS

The main sensors of the system that were used to indirectly measure the value of the plow pulling force in this research were deformation transducers. These sensors measure static and dynamic stresses. They are placed in pairs on the lower links of the tractor, so that the longitudinal axis of the sensor extends in the direction of the axis of the link. There are two sensors on each link, on both sides of the link, so it is possible to measure the stress during bending and stretching of the link, that is, to detect pressure and tension forces. There are a total of four sensors in the system, Fig. 1.

The measurement signal from the sensor is received and processed by means of the amplifier with eight inputs, Ethernet-based synchronization via IEEE1588:2008 (PTPv2) and 40 kS/s sample rate per channel, 7,2 kHz bandwidth.

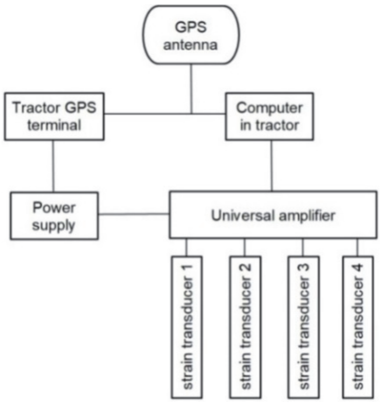

Figure 1 Scheme of measurement installation

The antenna signal is introduced into the computer via a specially designed adapter. Data processing is performed using CatmanEasi 4.2.2.14 software, produced by HBM. Additional data processing for mapping purposes was done with SPSS Statistics 21 software from IBM and SMS Advance from AG Leader Technology for mapping.

2.1 Prediction of the Pulling Force

For plowing measurements, a two-furrow plow with a total weight of 245 kg was used, while the power of the tractor was 82 kW. The soil behaves as an inhomogeneous system in terms of physical and chemical properties, so predicting the range and behavior of the traction force is very unpredictable.

Horizontal draft R_x varies depending on the method of soil tillage, size of attachment and implement, speed of motion and soil type. A number of methods have been developed for analytical evaluation of the attachment draft. Based on theoretical considerations and experiments, Goryachkin [31] developed an equation for the plough horizontal draft evaluation:

$$R_x = Gf + kabn + \varepsilon abnv^2 \tag{1}$$

The first term of this equation is frictional resistance, where, G, N represents plough weight and f is coefficient of friction. Average value of the coefficient of friction is in the range of 0,3 - 0,5 [32], however it can have higher value for compact soils.

The second term is the force required for cutting and deforming of a clod. Coefficient k, N/m^2 is soil specific resistance that depends on the soil type [33], parameter a, m is plowing depth, b, m is the plough body width, n is number of the plough bodies. Specific draft is determined by the soil type, soil moisture, ploughing depth, and plough body shape.

The third term of the equation denotes the force required to bring clod into motion and turn it over. Coefficient ε, Ns^2/m^4 depends on the plough body shape, soil properties and tractor speed v, m/s. This term increases as speed is increased. For speeds up to 5 km/h the value of the third term does not exceed 5% of the overall plowing resistance. Recommended plowing speeds are in the range of 5 - 10 km/h to achieve satisfactory plowing quality. Value of the coefficient ε ranges from 3000 to 10000 Ns^2/m^4 [34]. The impact of plough geometry on horizontal draft is given via the plough body width b. To precisely define the impact of geometry, an experiment has to be conducted [35].

Based on data presented in considering the assumptions and adopted parameters' values as follows: $f = 0{,}5$; $k = 5000$ N/m^2 (medium heavy soil sandy clay); $\varepsilon = 5000$ Ns^2/m^4, approximate value is obtained for the plough draft and tractor pulling force, respectively, which is used in the mapping procedure 9515 kN for the tillage depth of 20 cm.

Many researchers have dealt with defining the parameters that affect implement draft as well as with developing the equation that defines it. Results of their investigations have contributed to creating the equation for prediction of the implement horizontal draft D given by the ASAE D497.4 standard [36].

$$D = F_i\left(A + Bv + Cv^2\right)WT \tag{2}$$

where: F_i parameter determined by soil texture (i = 1, 2, 3 fine, medium coarse and coarse soil texture); A, B, C parameters determined by the implement type (tabular presentation, for a mouldboard plough $A = 652, B = 0, C = 5{,}1$); v, km/h tractor speed; W, m implement width; T, cm soil tillage depth. This standard can be used to assess plowing resistance, however changes in resistance amplitude can be caused by soil profile, texture, dynamics of tractor running up to ±50% [37].

Data presented in considering the assumptions and adopted parameters' values are used to obtain approximate value of the plough draft and tractor pulling force, respectively, that is used in the mapping procedure 9588 kN for the tillage depth of 20 cm.The value of force thus obtained does not deviate significantly from the value obtained using the Goryachin formula.

Field measurements are the most accurate methods of determining working machine draft. Due to such measurements, measuring instruments of various construction have been developed. Some of them are placed on specially designed frames to be embedded between the tractor and the working machine inside the tractor lift mechanism.

2.2 FEM Analysis and Calibration

Prior to installing strain transducers on the tractor lower links, strain state of the links was analyzed, Fig. 2a. The tractor link that was used for experimental measurements is two-component. Prior to installing sensors, part of the links directly connected to the plough needed to be machined by milling on both sides, four holes to be bored and cleaned, Fig. 2b.

Strain transducers work by force shunt measurement. It is therefore necessary to bolt the strain transducers to the lift arm in which the strains are to be measured. This sensor can detect link arm dilatation strictly longitudinally. For a reproducible measurement result, it is crucial for the contact surface of lift arm to be perfectly flat and free from distortion. The surface of the measurement lift arm must be sufficiently smooth (roughness $R_a \leq 3{,}2$). To measure a strain of 500 μm/m, the contact surface must be able to apply a force of about 3000 N to the measuring body. Fig. 2c shows sensors $ST2$ and $ST3$ on the inside of the links. Sensors $ST1$ and $ST4$ are on the outside of the links.

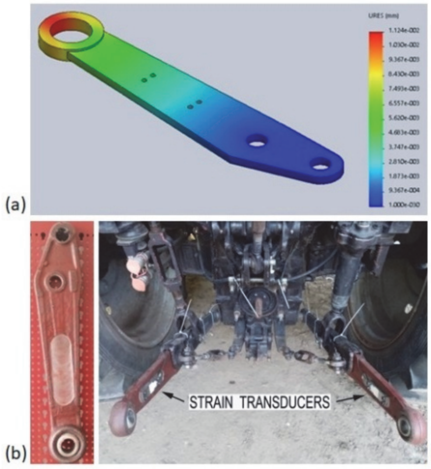

Figure 2 FEM analysis of the lift mechanism lower link (a), lower link prepared for sensor installing (b), sensors installed on the inside of lower links(c)

First, by calibration using some of the other voltage sensors or force's indication of the pulling force longitudinally, which corresponds to the soil draft component R_x,they are brought into connection with the output voltage. To that end, a force transducer, manufacturer HBM, type U1/5MP, calibrated according to the requirements of ISO 7500-1:2018 was used. Thereafter, correction factors were calculated. The tractor lower links were connected by a drawbar on which the described force transducer was installed. By successive tensile loading, approximate linear dependence was established between strain characteristics of the strain transducer expressed into mV/V and values of the force that manifests draft force measured using force transducer expressed into kN. It was found by calibration and then confirmed by measurements in the field that links are exposed to bending.

Correction factors established by calibration multiply the sum of dilatations individually on the outside and inside sensors, respectively, so that two values of the pulling forces are obtained:

$$F_o = \left(d_{ST1} + d_{ST4}\right)k_o \tag{3}$$

$$F_i = \left(d_{ST2} + d_{ST3}\right)k_i \tag{4}$$

where: F_o, kN pulling force measured using sensors on the outside of the links $ST1$ and $ST4$; F_i, kN pulling force measured using sensors on the inside of the links $ST2$ and $ST3$; $d_{ST1\text{-}4}$, mV/V dilatation of strain transducers $ST1$, $ST2$, *ST*3 and *ST*4, respectively expressed by output voltage; $k_o = -14,1$ kNV/mV calibration correction factor for calculating force using sensors *ST*1 and *ST*4; $k_i = 9,1$ kNV/mV calibration correction factor for calculating force using sensors *ST*2 and *ST*3.

Actually, coefficient k_o has negative value because sensors on the outside of lower links are under pressure loading. The draft force values will be additionally verified according to the values obtained by the Goryachkin approach or by standard ASABE Standard D497.4, 2003.

3 RESULTS AND DISCUSSION

Raw results for lower links strain measurements represent strain signals on the strain transducers. Prior to measurement, zero balance of all sensors was done while tractor was in an idle state with a plough lowered to the ground. Data was collected during plowing with the measurement resolution 50 Hz, but measuring resolution for the strain can be significantly lower. This way, 400 196 strain values were collected for each individual sensor. Dataset can be reduced in two ways without consequences for its use value and particularly precision of the maps themselves.The first way implies reduction of the draft measurement resolution. This especially makes sense because the update rate for GPS antenna is from 1 Hz to 10 Hz. The second way involves use of an additional sensor, e.g., proximity switch. The application of new sensors enables distinction between the operating state where tractor-machine unit is occupied during plowing operation or any other operation across the field with lowered links and active working organs in relation to the intermediate state when turning the tractor on a headland in which case the tractor links are lifted and working machine is not in contact with the soil. The real-time graphs shown in Fig. 3 depict the variation in output voltage between the different strain transducers.

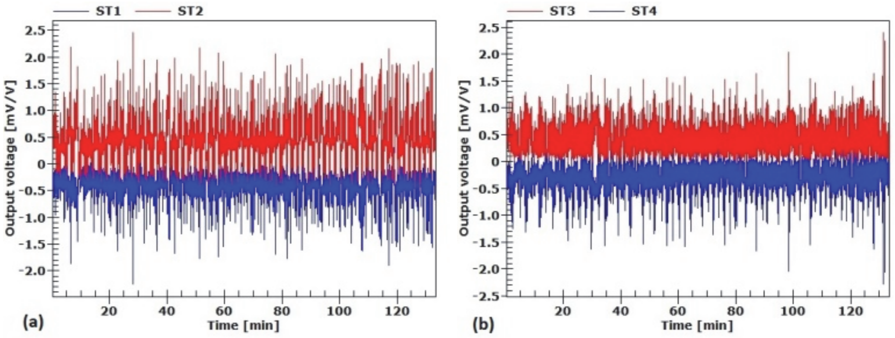

Figure 3 Representative time domain signal of output voltage signal for strain transducers on the tractor left (a) and right lower link (b)

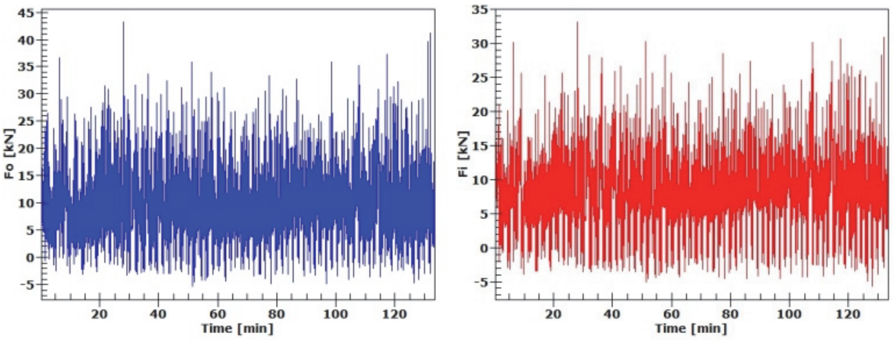

Figure 4 Representative real-time graphs of pulling force across the entire experimental field

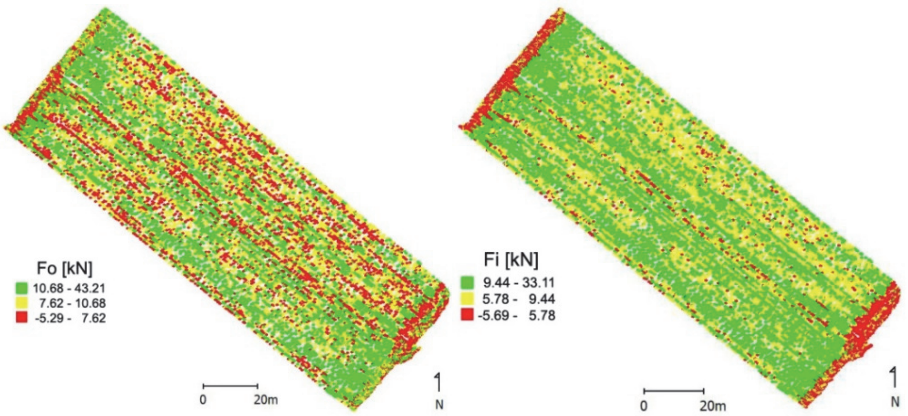

Figure 5 Pulling force maps along the entire field

Output voltage range of strain transducers *ST*1 and *ST*4 (Fig. 3, marked with blue color) are mostly negative, only a small part of the data range is positive and the opposite goes for strain transducers *ST*2 and *ST*3 (Fig. 3, marked with red color). Based on values collected from sensors, the calculations are applied to obtain values of draft forces themselves during the entire process of plowing the experimental field using Eq. (3) and Eq. (4). Distribution graph of these forces in the time domain is shown in Fig. 4. Based on these values, it is also possible to perform preliminary mapping of the pulling force, which will contain, too, values of the forces on the lower links when work starts or stops on headlands, Fig. 5.

The maps clearly show red zones at the ends of the field, where the force in the links is close to zero in its value, because there is not soil resistance, or it gradually increases when the plough enters the furrow, or it gradually decreases when the plough gets out of the furrow. Also, in these areas, the assumptions about the constancy of the speed of motion and plowing depth at the ends of the field are not fulfilled.

In order to gain a more realistic insight into the draft force and to ensure the fulfillment of assumptions, software was used to create a new area within the current plowed part of the field 120 m in length. New control limits are within the field and do not include its ends and headlands. Further analysis of the draft force and statistical analysis of measured values will be performed strictly within these control limits. This caused the reduction of dataset so that further processing is conducted on a set of 195 040 consecutive values of the output voltage of strain transducer and the pulling force. On a large sample of data, the distribution is not expected to be normal. Diagrams in Fig. 6 represent the output signal on all four strain transducers but this time only within the control limits in the field. When sensor readings at the ends of the plot are eliminated, the obtained signal is considerably clearer, especially in the vicinity of the zero level of the voltage values readings and with a smaller amplitude range than the voltage signal describing the entire field (Fig. 3). Thereafter, diagrams and maps of pulling forces are given, obtained using two pairs of sensors, Fig. 7. It is only based on these indicators that it is possible to perform more realistic analysis of the presented method of site-specific mapping of draft force, Fig. 8.

Diagrams and maps represent visually very similar spatial variations of draft force. Limits of medium range in both maps have similar values. Statistical analysis will be employed to check the level and statistical significance of correlation between these two maps.

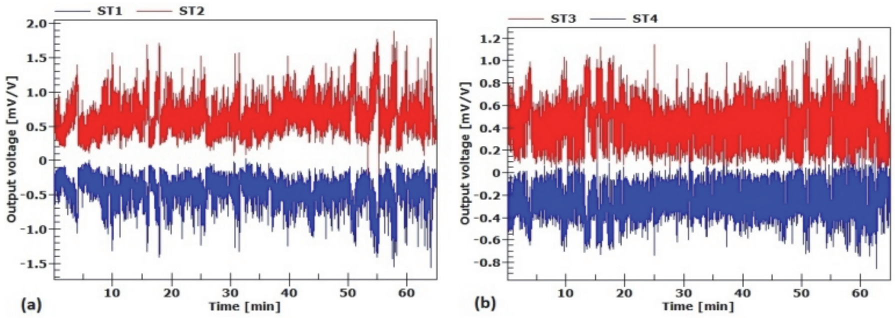

Figure 6 Representative time domain signal of output voltage for strain transducers on the tractor left (a) and right lower link inside control limits (b)

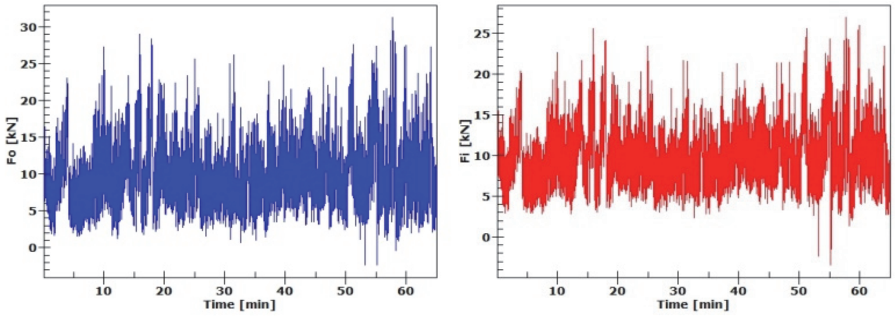

Figure 7 Representative real-time graphs of pulling force and soil resistance inside control limits

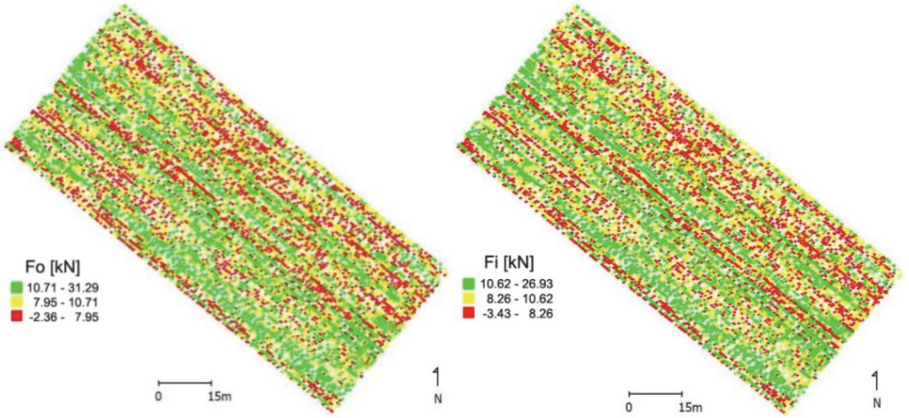

Figure 8 Maps of pulling force inside control limits

The pulling force maps within the control limits shown in Fig. 8 justify the introduction of control limits. These maps suggest the existence of longitudinal zones as a result of measuring pulling force in the direction of tractor movement, but unlike the corresponding maps shown in Fig. 5, there are no zones at the ends of plots with reduced pulling force. This eliminates the cases of initial penetration of the plow into the soil or its final removal from the soil when the measurement results are not relevant due to depth deviations. The ends of the parcels, both in width and in length, can always be a source of inaccuracy in different types of measurements and conclusions, and they should always be considered separately, if possible.

4 CONCLUSION

The maps clearly indicate that the pulling force values change across the field width, i.e., they weakly change longitudinally and follow individual passes. Also, it is observed that the maps do not match quite in terms of value if zoning is performed with one third of data each from the whole range, but the tendencies of local change in pulling force are very similar in both maps. However, both maps significantly lose their meaning due to measuring force in the links on headlands when the plough is inactive.

When measuring pulling force, any insistence on measurement accuracy drastically increases the cost of the equipment and increases the time spent on installation and calibration of the equipment. On the other side, the verifiability of the measurement precision is highly debatable, because the soil always behaves as a stochastic system. These are the reasons why research efforts should most optimally be directed to finding methods for optimal measurement of soil resistance variability and consequently traction force. It is precisely the observed variability that is easiest and most expedient to use to further increase yields or make agricultural production cheaper.

Sensors for measuring force during plowing must have the necessary sensitivity to record all the variables, but they also need to be robust enough due to the specific working conditions. A significant result of this paper is also a successful mapping of soil resistance based on confirmed and measured variation of resistance value that was really within the limits of resistance amplitude variation up to ±50% as prescribed in the paper [37].

The machines that move during the season on the plot are certainly the first cause of soil compaction. It is advisable to overlap the pulling force maps with the maps of permanent passes in order to see the impact of machine wheel tracks on soil compaction. After that, pulling force maps can be considered in correlation with other types of maps or used as one of the possible layers in the formation of prescription maps, primarily for the regulation of sowing depth.

Other operations in the field of precision agriculture were also undertaken on the sample farm during the growing season. Maps of pulling force show similarity with crop scouting maps and clear changes in values according to crop rows along the plot. The soil electromagnetic conductivity map suggests relatively good soil conductivity and relatively low variability of this conductivity across the sample field, but without corelation with pulling force maps.

Acknowledgements

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5 REFERENCES

[1] Fröba, N. (1995). Benötigte Traktor Motorleistung bei landwirtschaftlichen Arbeiten. *KTBL Arbeitsblatt Nr. 0255 in Landtechnik, 50*(5), 277-282.

[2] Cerovic, V., Milkovic, D., Grbovic, A., Petrovic, D., & Simonovic, V. (2020). 2D Analitical Model for Evaluation of the Forces in the Three-point Hitch Mechanism. *Journal of Agricultural Sciences Tarim Bilimleri Dergisi, 26*(3), 271-281. https://doi.org/10.15832/ankutbd.493339

[3] Jabro, J. D., Stevens, W. B., Iversen, W. M., & Evans, R. G. (2010). Tillage Depth Effects on Soil Physical Properties, Sugarbeet Yield, and Sugarbeet Quality. *Commun. Soil Sci. Plant Anal., 41*, 908-916. https://doi.org/10.1080/00103621003594677

[4] Lee, K. S., Park, J. G., Cho, S. C., Noh, K. M., & Chang, Y. C. (2007). Physical Properties of Hardpan in Paddy Fields. *J. Biosyst. Eng., 32*, 207-214. https://doi.org/10.5307/JBE.2007.32.4.207

[5] Ortopan, M., Simonovic, V., Tasic, N., Veg, E., Zlatanovic, I., & Gubeljak, N. (2024). Analyzing Site-specific Tractor Draft Force in Different Passes during Plowing. *Technical Gazete, 31*(1), 228-232. https://doi.org/10.17559/TV-20230614000733

[6] Gebresenbet G. (1992). Dynamic Effects of Speed, Depth and Soil Strength upon Forces on Plough Components. *J. agric. Engng Res, 51*, 47-66. https://doi.org/10.1016/0021-8634(92)80025-N

[7] Al-Suhaibani, S. A. & Ghaly, A. E. (2010). Effect of Plowing Depth of Tillage and Forward Speed on the Performance of a Medium Size Chisel Plow Operating in a Sandy Soil. *American Journal of Agricultural and Biological Science, 5*(3), 247-255. http://doi.org/10.3844/ajabssp.2010.247.255

[8] Hunt, D.(1973). Farm power and machinery management. *6th ed. Iowa State University Press*, Ames, Iowa.

[9] Eidet, J. H. (1974). Effect of varied approach-angle on high speed plow performance. *Unpublished M.S. Thesis*. Iowa State University, Ames, Iowa, USA.

[10] Inchebron, K., Mousavi Seyedi, S. R., & Tabatabaekoloor, R. (2012). Performance evaluation of a light tractor during plowing at different levels of depth and soil moisture content. Int. *Res. J. Appl. Basic Sci, 3*(3), 626-631.

[11] Rashidi, M., Najjarzadeh, I., Jaberinasab, B., Emadi, S. M., & Fayyazi, M. (2013). Effect of soil moisture content, tillage depth and operation speed on draft force of moldboard plow. *Mid.-E. J. Sci. Res, 16*(2), 245-249.

[12] Collins, B. A. & Fowler, D. B. (1996). Effect of soil characteristics, seeding depth, operating speed, and opener design on draft force during direct seeding. *Soil Till. Res, 39*, 199-211. https://doi.org/10.1016/S0167-1987(96)01062-8

[13] Stuchly, S. S., Townsend, J. S., & Thansandote, A. (1976). Travel Reduction Measurement by Doppler Radar Methods. *ASAE*, *76-1070*, St. Joseph, Michigan, USA.

[14] Freeland, R., Tompkins, F., & Wilhelm, L. (1988). Portable Instrumentation to Study Performance of Lawn and Garden Ride-On Tractors.*ASAE, 88-1079*, St. Joseph, Michigan, USA.

[15] Wang, Z. & Domier, K. W. (1989). Prediction of Drawbar Performance for a Tractor with Dual Tires. *Transactions of the ASAE, 32*(5), St. Joseph, Michigan, USA. https://doi.org/10.13031/2013.31184

[16] Khalilian, A., Hale, S., Hood, C., Garner, T., & Dodd, R. (1989). Comparison of Four Ground Speed Measurement Techniques. *ASAE, 89-1040*. St. Joseph, Michigan, USA.

[17] Grisso, R., Taylor, R., Way, T., & Bashford, L. (1991). Tractive Performance of 18.4R46 and 18.4R42 Radial Tractor Tires". *ASAE, 91-1589*. St. Joseph, Michigan, USA.

[18] Reed, J. & Turner, P. E. (1993). Slip Measurement Using Dual Radar Guns. *ASAE/CASE, 93-1031*.

[19] Zoerb, G. C. & Popoff, J. (1967). Direct indication of tractor-wheel slip. *Canad. Agric. Eng., 9*(2), 91-93.

[20] Lyne, P. W. & Meiring, P. (1977). A wheel slip meter for traction studies. *Trans. ASABE, 20*(2), 238-242. https://doi.org/10.13031/2013.35532

[21] Clark, J. S. & Gillespie, J. R. (1979). Development of a Tractor Performance Meter. *ASAE, 79-1616*, St. Joseph, Michigan, USA.

[22] Jurek, R. L. & Newendorp, B. C. (1983). In-Field Fuel Efficiency Comparisons of Various John Deere Tractors. *ASAE, 83-1563*, St. Joseph, Michigan, USA.

[23] Grevis-James, I. W., DeVoe, D. R., Bloome, P. D., & Batchelder, D. G. (1981). Microcomputer Based Data Acquisition System for Tractors. *ASAE, 81-1578*, St. Joseph, Michigan, USA.

[24] Erickson, L., Larsen, W., & Rust, S. (1982). Four-Wheel Drive Tractor Axle and Drawbar Horsepower: Field Evaluation and Analysis. *ASAE, 82-1057*, St. Joseph, Michigan, USA.

[25] Shropshire, G. J., Woerman, G. R., & Bashford, L. L. (1983). A Microprocessor Based Instrumentation System for Traction Studies. *ASAE, 83-1048*, St. Joseph, Michigan, USA.

[26] Musonda, N. G., Bigsby, F. W., & Zoerb, G. C. (1983). Four Wheel Drive Tractor Instrumentation.*ASAE, 83-1546*, St. Joseph, Michigan, USA.

[27] Bulgakov, V., Adamchuk, V., Nadykto, V., Kistechok, O., & Olt, J. (2017). Theoretical research into the stability of motion of the ploughing tractor-implement unit operating on the 'push-pull' principle. *Agronomy Research, 15*(4), 1517-1529.

[28] Al-Hamed S. D., Grisso, R. D., Zoz F. M., & Von Bargen K. (1994). Tractor performance spreadsheet for radial tiers, *Computers and Electronics in Agriculture, 10*, 45-62. https://doi.org/10.1016/0168-1699(94)90035-3

[29] Schreiber, M. & Kutzbah, H. D. (2008). Influence of soil and tire parameters on traction. *Research in Agricultural Engineering*, 54, 43-49. https://doi.org/10.17221/3105-RAE

[30] Sümer, S. K. & Sabanaci, A. (2005). Effects of Different Tire Configurations on Tractor Performance. *Turkish Journal of Agriculture and Forestry, 29*, 461-468.

[31] Горячкин, В. П. (1968). *Сабрание сочинений, 2-е изд.* Москва, Колос, 456.

[32] Bernacki, H., Haman, J., & Kanafojski, Cz. (1972). Agricultural machines: theory and construction. *Scientific Publications Foreign Cooperation Center of the Central Institute for Scientific, 883*.

[33] Martinov, M. & Markovic, D. (2002). *Machines and implements for soil tillage*. Faculty of Technical Sciences of Novi Sad, Novi Sad.

[34] Musil, J. & Cervinka, J. (2007). Measuring of pulling resistance in machinery with passive working organs. *Research Argicultural Engineering, 53*(2), 47-53. https://doi.org/10.17221/2121-RAE

[35] Plouffe, C., McLaughlin, N. B., Tessier, S., & Laguë, C. (1995). Energy requirements and depth stability of two different moldboard plow bottoms in a heavy clay soil. *Canadian Agricultural Engineering, 37*(4), 279-285.

[36] ASAE Standard D497.4. (2003). Agricultural Machinery Management Data. *ASAE*, St. Joseph, Michigen, USA.

[37] McLaughlin, N. B., Drury, C. F., Reynolds, W. D., Yang, X. M., Li, Y. X., Welacky, T. W., & Stewart G. (2008). Energy inputs for conservation and conventional primary tillage implements in a clay loam soil. *Transaction of the ASABE, 51*(4), 1153-1163. https://doi.org/10.13031/2013.25231

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