Measurement of Strain Induced on a Deep Placement Fertilizer Applicator by Static load and Finite Element Simulation

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Abstract. This paper briefly reveals study results performed on a deep placement fertilizer applicator (DPFA) in order to measure strain gage resistances and calibrate a strain gage piece of equipment in laboratory conditions. The finite element method (FEM) simulation was performed in order to identify stress concentrated areas by strain gage attachments, and to determine optimum material properties for a DPFA prototype fabrication. New laboratory arrangements and theories of resistance force determination of a DPFA were developed in order to simulate different soil depths (0.15, 0.20, 0.25m) and apply a static load (5000N) in laboratory conditions. Unique practical knowledge was obtained in terms of different strain gage applications on the DPFA in its rigid form to obtain strain gage resistances. It was found that the strain sensitivity of the strain gages depended on the work dimensions of strain gage characteristics.

Keywords: Deep placement fertilizer applicator; static load; FEM; strain gage; soybean cultivation

1. Introduction
The development of new machinery and technologies in agriculture is one of the key functions in sustainable production. Nowadays, agricultural machinery manufacturers produce machinery and tools (e.g. conventional plows, harrows, chisel plows, etc.) with significant quantity and excessive design (e.g. over mass, size, and safety factors) [1]. Therefore, improvement by way of streamline design would significantly reduce the amount of used material and the final cost.

Deep placement fertilizer applicators (DPFA) are still one of the most important issues in developing agricultural tools in new agricultural machinery. Currently, the development of a DPFA has become a key point in utilizing a deep placement fertilizer technology (DPFT) in crop production. Since the DPFT
is an advanced and cost-effective method, which serves not only in decreasing the wastage and excessive use of fertilizer, but also in the even supply of nutrition in the soil and the mitigation of the negative effects caused by fertilizer applications on the environment [2]. In Addition, the subsoil tillage by the DPFA may significantly enhance crop growth through the tillage of compacted soil layers which provides free air and water exchange. Additionally, it increases labor-savings by the effect of slow-release fertilizers [3-4].

To apply the DPFT during crop planting, new DPFAs need to be developed for subsoil tillage with simultaneous application of slow-release fertilizer. Although several studies have been effectively carried out on deep placement fertilizer machinery and subsoiler tools [5-8], there is limited practical knowledge on the usage of DPFT and design optimization of DPFA. Thus, this study was carried out in order to obtain practical knowledge of a DPFT for soybean cultivation in Primorsky Krai (PK), Russia. Moreover, the results of this study will be used for future machinery development in terms of shape, streamline design and the reduction of excessive design.

The main purpose of this study was to measure strain resistances by applying a static load on a DPFA with attached strain gages in laboratory conditions. These measurements are needed to obtain data on strain gage resistance and calibrate strain gage equipment before field experiments to calculate traction resistance and soil resistance. Another purpose was to perform a simulation on the DPFA to evaluate the mechanical behavior by stress and strain analysis of the static simulation through the Finite Element Method (FEM). This simulation was needed to acquire the locations of stress concentrations on the DPFA where strain gages can be attached for practical experiments.

2. Materials and Methods

2.1 Designed DPFA

This study was based on a chisel plow model, which was made by Sandakov et al. [8]. The model was excessively designed and used for subsoil cultivation. However, we have designed a new DPFA plow, which is not only satisfactory with our technical issues for soybean cultivation but meets the issues of conserving resources due to its streamline design (Figure 1).

![Figure 1. Designed DPFA, (mm)](image)

- a – frame connector height; b – shank width; h – shank height; K – knife length; k – knife width; R – curvature radius of the shank; d – penetration angle; F – fertilizer pipe inlet; t – shank thickness

The main issues were to achieve deep tillage and simultaneously apply fertilizers into the soil at a depth of 0.15, 0.20 and 0.25m. In addition to this, the fertilizer pipe attached to the chisel shank should
not increase the tractive resistance made by the chisel plow. In the case of the tractive resistance, we
decided to make a fertilizer pipe with a round inlet and square outlet, attaching it on the back of the plow
to avoid resistance from the front.

2.2 FEM
To evaluate the mechanical behavior of the DPFA and acquire the stress locations for strain gage
attachments, several types of FEM analysis were used, including structural and stress analysis depending
on the variable loads applied. This FEM simulation software (Fusion 360 by Autodesk, Inc.) was used
in collaboration with an advanced computer aided design (CAD), which is commonly implemented in
the agricultural engineering industry for design and manufacturing processes [9].

According to the previous study, the static force induced on a chisel plow meets the dynamic force
at targeted soil depths of 0.3, 0.35 and 0.4m and at operating speeds of 4, 4.5 and 5km/h, respectively
[8]. Therefore, due to the heavy soil property in PK (clay soils with 25–40% of clay), and our experience,
6000N has been considered as a maximum static load for the FEM simulation.

2.3 Laboratory setup
A laboratory setup was developed to simulate and apply the static load to the DPFA in laboratory
conditions. Figure 2 shows the main features of the laboratory setup.

![Figure 2. Laboratory setup](image)

1 – metal worktop; 2 – adjustable boundary conditions of bolt connectors; 3 – applied force centers; 4
– dynamometer (5000N); 5 – adjustable load turnbuckle; 6 – adjustable bracket depth

The main idea of the laboratory arrangement was to fix the DPFA on a worktop and apply an interval
static load. This configuration was made on a metal worktop, and all parts were fixed by an arc welding.
In order to simulate the different frame fixations of the DPFA, we used two adjustable cylinders (Figure
2 (2)) with a diameter of 19mm. Furthermore, to simulate different soil depths (0.15, 0.20 and 0.25m),
we determined force (loads) centers (Figure 2 (3)).

2.4 Strain gage equipment
The strain gages attached to the DPFA, data logger amplifier with data acquisition software and the
bridge box were manufactured by Kyowa Electronic Instruments Co., Ltd. Japan.

Two types of foil strain gages (KFGS-30-120-C1-11 L5M2R and KFGS-20-120-C1-11 L5M3R) were used with the 2 and 3-wire systems, as well as different gage widths and lengths in order to capture
and identify different strain resistances. The EDX-100A-4 data logger amplifier with the DCS-100A
data acquisition software was used to record data manually and periodically with different time
intervals. The one-touch type bridge box (DBV-350A-8) was used to connect the strain gages with the data logger amplifier.

3. Results and Discussion

3.1 FEM Simulation

Once the design was completed, a 3D model was generated. It performed a static analysis using the software AutoCAD Fusion 360. This simulation showed the specified areas with a different range of colors to visualize the material’s behavior of the DPFA under different types of loads and boundary conditions. Thus, the optimum material property for the DPFA fabrication, and maximum stress locations where the strain gages were attached were determined. Figure 3 shows the boundary conditions and the areas of applied stress.

![Figure 3. FEM simulation](image)

In real subsoil conditions, a soil load will be evenly distributed throughout the subsoil area of the DPFA, thus in the FEM simulation, different loads were applied on the maximum load surface areas of the knife. Therefore, we simulated a different DPFA fixation depending on different soil depths as shown in figure 3 (a). Moreover, the FEM simulation showed the most stressed areas (Figure 3 (b)), where we attached the strain gages to obtain strain gage resistances and calibrate all strain gage equipment. In addition, by multiple experiments, we have determined the material properties of the DPFA to have optimum yield and ultimate strength. The determined optimum material properties of the DPFA are presented in Table 1.

| DPFA parts | Shank and Knife | Fertilizer pipe |
|------------|----------------|-----------------|
| Material   | High strength steel | Common steel |
| Young’s modulus (MPa) | 207×10³ | 205×10³ |
| Poisson’s ratio   | 0.33 | 0.29 |
| Yield strength (MPa) | 780 | 207 |
| Ultimate strength (MPa) | 950 | 345 |
| Maximum stress (MPa) | 379.9 | 150.1 |
| Maximum strain (mm/mm) | 25.6×10⁻⁴ | 11.3×10⁻⁴ |
| Mass (kg) | 11.2 | 0.58 |
Next, based on the results of the simulation and material properties, a DPFA prototype was manufactured and strain gages were attached for laboratory experiments. Figure 4 illustrates a manufactured DPFA with attached strain gages fixed to the laboratory setup.

3.2 Determination of resistance force of DPFA

By the FEM simulation in the CAD Fusion software, the results were obtained, however, to simulate the static load and determine the strains induced on the DPFA in laboratory conditions, it was necessary to determine the centers of application of a resultant force depending on the different soil depths. A resultant force is a force acquired by combining a system of forces on a rigid body. The defining feature of a resultant force is that the resultant force has the same action on the rigid body as the initial system of forces [10].

Accepting the assumption, that the soil resistance force applied to the DPFA is proportional to the front area of the DPFA. In this case, we used the method of determining the centers of parallel forces on the DPFA, such as the method of determining the gravity center of the rigid bodies.

We divide the front area of the DPFA (the front area of the DPFA is perpendicular to the axis of soil movement) into three geometric figures, symmetrical to the vertical axis. Figure 5 illustrates the scheme of the determined centers of a resultant force application depending on the different soil depths with all dimensions for calculation.

![Figure 5: Scheme of a resultant force application depending on the different soil depths (mm)](image)

1 – triangle of the bottom knife part; 2 – rectangle of the top knife part; 3 – rectangle of the shank
According to the scheme (Figure 5), we determined the coordinates of the centers C1, C2, C3 of the application of resistance forces of individual sections (1, 2, 3) of the DPFA, along the Oy axis as follows: \( C1 = 10; \ C2 = 32.5; \ C3 = 150 \) for soil depth of 0.25m (C1 and C2 have unchanged values, C3 has a variable value, depending on the soil depth).

To determine the center of application for the resistance force on the DPFA, we used the formula for determining the center of parallel forces (center of gravity) [11], as follows:

\[
YC = \frac{1}{S_{Total}} \sum (YC_i \cdot Si)
\]

where: \( YC \) is the general center of application of the resistance force on the DPFA; \( S_{Total} \) is the total area of the DPFA (front area applied in the soil), mm²; \( YC_i \) are coordinates of the resistance force center of each DPFA areas, mm; \( Si \) is the area of each section of the DPFA, mm².

A brief example of the calculation for 0.25m applied force center is given below:

\[
YC_{0.25} = \frac{YC_1 \cdot S_1 + YC_2 \cdot S_2 + YC_3 \cdot S_3}{S_1 + S_2 + S_3}
\]

Where: \( S_1 = 510 \) and \( S_2 = 2380 \) are areas of individual geometric shapes of the knife (Figure 5 (1, 2)), mm²; \( S_3 = 4800 \) is the area of the shank (Figure 5 (3)), mm². However, according to the figure 5 (b, c), the coordinate of the center resistance force will be changed, and the area \( S_3 \) (which is the rectangle of the shank) will be decreased.

\[
YC_{0.25} = \frac{10 \cdot 510 + 32.5 \cdot 2380 + 150 \cdot 4800}{510 + 2380 + 4800} = 104.4 \text{mm}
\]

By the calculation, three applied force centers were obtained for the shank, and one center for the knife of the DPFA depending on the soil depth. Thus, for the laboratory experiment, we applied a static load on the force centers (Figure 2 (3)) at a distance from the lower part of the DPFA (\( YC_{0.25} = 104.4 \text{mm} \); \( YC_{0.20} = 82 \text{mm} \); \( YC_{0.15} = 61 \text{mm} \)) for the shank, and (\( Yk = 28.5 \text{mm} \)) for the knife.

3. Strain gages resistance result

By using the laboratory configuration (Figure 2), the static load 5000N was applied with an interval of 500N stepwise, and data recording was done manually. Three unique strain gage resistances were obtained depending on the simulation of different soil depths. Figures 6 and 7 show the results of obtained strain gage resistance by two different strain gages attached to the upper part of the shank. The negative (−) direction of the strain gage’s resistance shows that a foil strain gage deforms in the reverse direction.

![Figure 6. Strain gage resistance of KFGS-30-120-C1-11 L5M2R](image-url)
Due to the different strain gage characteristics, especially gage width and length, we can notice that there is an entirely different resistance sensitivity under the same experimental conditions. Moreover, the strain gage with wider gage width (KFGS-20-120-C1-11 L5M3R) shows not a significant difference in the resistance between different simulation conditions. However, during the measurements, it was noticed that the KFGS-20-120-C1-11 L5M3R had fewer noises in comparison with the KFGS-30-120-C1-11 L5M2R which showed more stability in terms of data recording. These effects of noises can be explained by the different wire systems and connections between the strain gage and bridge box. Figure 8 shows the difference between the two strain gages (gage characteristics (Grid)) attached to the upper part of the shank of the DPFA.

We can conclude that in order to capture more accurate strains induced by a load in a rigid body, it is better to use the strain gages with a longer gage length since it leads to obtaining accurate strains. Plus, the 3-wire gage connection system will help to avoid unnecessary noises and measurement errors. For further field experiments to calculate traction resistance of the DPFA and soil resistance induced on a subsoil area, we consider using the strain gages (KFGS-30-120-C1-11), however, with the 3-wire system.
4. Conclusion
This study was focused on the DPFA to evaluate the mechanical behavior through stress and strain analysis of the static simulation by FEM, and perform a laboratory experiment to obtain data on strain gage resistances and calibrate strain gage equipment before field experiments.

In the FEM simulations were found the most stressed areas from where we attached the strain gages for laboratory experiments. Plus, the FEM determined the material properties of the DPFA with optimum yield and ultimate strength. The laboratory experiments and theory of resistance force determinations were developed to obtain strain gage resistance, and calibrate strain gage equipment. Practical knowledge was obtained in terms of different strain gage characteristic types. It was found that the strain sensitivity depends on the work dimensions of a strain gage. Additionally, the wire gage connection system affects the accuracy of the data recorded by the reduction of noises.

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References
[1] Yurdem H, Degirmencioglu A, Cakir E and Gulsoyulu E 2019 Measurement of strains induced on a three-bottom moldboard plough under load and comparisons with finite element simulations Measurement 136 pp 594-602
[2] Yao Y, Zhang M, Tian Y, Zhao M, Zhang B, Zhao M and Yin B 2018 Urea deep placement for minimizing NH3 loss in an intensive rice cropping system Field Crops Research 218 pp 254-266
[3] Topakci M, Celik H K, Canakci M, Rennie A E, Akinci I and Karayel D 2010 Deep tillage tool optimization by means of finite element method: Case study for a subsoiler tine Journal of Food, Agriculture & Environment 8(2) pp 531-536
[4] Fujii T, Hasegawa H, Ohyama T and Sinegovskaya V T 2015 Evaluation of tillage efficiency and power requirements for a deep-placement fertilizer applicator with reverse rotational rotary Russian agricultural sciences 41(6) pp 498-503
[5] Ahamed M S, Ziauddin A T M and Sarker R I 2014 Design of improved urea super granule applicator. Int. J. Appl. Science and Engineering Research 3(1) pp 98-104
[6] Hang C, Gao X, Yuan M, Huang Y and Zhu R 2018 Discrete element simulations and experiments of soil disturbance as affected by the tine spacing of subsoiler Biosystems Engineering 168 pp 73-82
[7] Ebrahimi R, Mirdamadi H R and Ziaei-Rad S 2018 Operational modal analysis and fatigue life estimation of a chisel plow arm under soil-induced random excitations Measurement 116 pp 451-457
[8] Sandakov T, Sandakova N, Chang L, Hasegawa H and Radnaev D 2019 Optimum design of a chisel plow for grain production in the Republic of Buryatia, Russian Federation AMA, Agricultural Mechanization in Asia, Africa and Latin America 50(1) pp 73-78
[9] Celik H K, Caglayan N, Topakci M, Rennie A E and Akinci I 2020 Strength-based design analysis of a Para-Plow tillage tool Computers and Electronics in Agriculture 169 pp 105168
[10] McCarthy J M and Soh G S 2010 Geometric design of linkages Vol 11 Springer Science & Business Media
[11] Lachuga Y F and Ksendzov V A 2010 Theoretical mechanics (Moscow: Kolos) p 576