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Embodiment design of a soil bin for soil-tool interaction study

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Abstract. The agriculture industry is an important aspect of Indian economy. The changes occurring in global climate and increased frequency of extreme weather conditions pose challenges for agriculture industry. In such unpredictable conditions, achieving required outputs from farming for supporting continuously increasing population necessitates the mechanization of traditional processes. The selection of machinery for such mechanized setup is a key management task. Tractor is one of the farm machines being used in various farm related operations. Thus understanding constraints imposed on selection of a tractor is a primary factor in decision making process. The study has highlighted importance of power requirement for farming operation in tractor selection process. Thus to determine power requirement for farming operation a study of soil-tool interaction is necessary. A soil bin setup is one of the tools for studying the soil-tool interaction. This work presents the conceptual and embodiment design of a soil bin developed to find variation in draft force with respect to variations in the parameters like tillage depth, operation speed and soil moisture level. The tillage depth and operation speed were found to be directly proportional whereas the soil moisture level was found to be inversely proportional to the draft force.

1. Introduction

In any business domain, optimum utilization of available resources has always been an important task. The field of agriculture also requires a similar optimization in resource utilization for farming operation. In a mechanized agriculture setup, the mechanical power is itself an important resource. In order to use this resource efficiently, it is necessary to select suitable machinery for farming operations. In a mechanized agriculture setup, the tractor is the commonly used farm machinery for providing mechanical power for performing tillage operation. The soil tillage is one of the farming related applications where the soil cutting tool or implement interacts with soil. From the agricultural point of view the soil tillage can be defined as the mechanical soil manipulation which is essential for achieving the required soil conditions which are necessary for adequate plant growth and crop production. The proper land preparation or soil tillage can result in an effective and a profitable crop production. As discussed by Manian et al. [1], tillage being the major activity in the process of crop production, it consumes almost 30 to 35% of the total energy required for an agricultural setup. The tillage tools or implements are mechanical devices which are used for soil preparations. These implements cause cutting, inversion, pulverization, movement or mixing of the soil as the forces are applied to the soil to simultaneously. The draft is the force required by implement for overcoming the resistance offered by soil to the movement of implement. The determination of draft force requirement thus plays an important role in deciding the power required for the soil manipulation operation. A variety of models for draft prediction have been proposed by researchers.



Plouffe et al. [2] studied the effect of operation speed and tillage depth on two types of moldboard plows. Kheiralla et al. [3] developed a draft prediction model for moldboard plough, disk harrow, disk plough and rotary tiller. The model used operation depth, operation speed as input variables for regression model. Sahu and Raheman [4] discussed a draft prediction approach where a draft equation was developed using tillage depth, speed, wet bulk density and cone index as input parameters. Abbaspour et al. [5] performed an investigation for determining the effects of tractor speed, soil texture, soil moisture and electrical conductivity on tillage energy requirement and fuel consumption. Karmakar et al [6] conducted a study of soil tool interaction with help of an experimental setup. Naderloo et al. [7] studied the effect of tillage depth and forward speed on tillage implements. Al-Suhaibani and Ghaly [8] [9] studied the effect of plowing depth and forward speed on medium size chisel plow performance. Rashidi et al. [10] [11] [12] investigated the effect of soil moisture content, tillage depth and forward speed on draft force. Al-Hamed et al. [13] proposed the use of artificial neural network model for prediction of draft and energy requirement of disk plow. Mari et al. [14] investigated effect of soil forces for different working conditions on the surface of moldboard plow. Mohammadi et al. [15] used a simulation of winged shared tillage tool for draft force prediction. Ranjbarian et al. [16] studied performance of tractor and tillage implements in clay soil and found that increase in forward velocity results in increase of implement draft. Mari et. al. [17] conducted a laboratory experiment for effect of tillage operation on paddy soil. Deshpande et al. [18] studied the effect of variation in forward speed, operating depth and type of tool on draft force, specific draft and soil disturbance parameter.

Armin et al. [19] underlined the importance of soil-tool interaction study for optimal design of farm equipment. Yang et al. [20] developed tillage and seeding implement testing facility. Mustafa et al. [21] studied the moldboard plow in form of a scaled down model. The experiments were carried out in soil bin of dimension 90cm length, 50 cm width and 17 cm depth. Ranjbarian et al. [16] developed a mobile instrument for measuring the performance parameters of the tractor and attached implements. In most of these soil-tool interaction studies, the implement or the tool was moved relative to the soil. Some of the experimentation was performed in actual field while some studies were conducted in controlled environments with help of an experimental setup. Such experimental setup used for soil-tool interaction study is a soil bin. The soil bin investigation of tillage tools can help in development of tillage tools and support in performance improvement these tools. A typical soil bin systems can aid in understanding the soil-machine interaction through the experiments performed under controlled conditions.

2. Role of Soil Bin in Soil-Tool Interaction Study

The evaluation of soil-tool interaction involves the studies for understanding the effect of various parameters related to operation and operating conditions, on the tool-soil system. The tool performance is usually evaluated by means of the draft force, vertical force and lateral force. All of these forces are exerted on the tool by the soil. According to Reaves et al. [35] and Soltynski [36], the tool parameters, soil parameters, tool-soil interface parameters and surcharge conditions are the four groupings possible for the operating conditions variables. The tool depth, width, rake angle, speed of operation, aspect ratio and shape of the tool are included under tool parameters. The soil factors are comprised of cohesion, angle of internal friction, bulk density, and moisture content. The parameters such as soil-metal friction angle, adhesion, tool sharpness and wear conditions are considered as a subset of parameters related to interface of the tool and the soil interaction domain. Surcharge condition parameters are important, but these parameters are considered only in the cases where the tool operates completely below the soil surface. Such conditions are usually represented with help of a uniform pressure being applied on the surface of the tool. The parameter evaluation for soil-tool interaction thus involves evaluation of multiple parameters and such evaluation necessitates the use of testing facility where soil-tool interaction can be studied.

The soil bin is a facility which can facilitate the soil-tool interaction study. The soil bin facility is also a tool for testing of scale model and conduct experiments for studying the soil-machine interaction. Soil bins have been used for not only testing soil engaging tools but also for materials incorporation tools. The soil engaging tools include instruments like tillage tools and seeding openers. The materials

incorporation tools include the farm operation tools like manure injection tools, straw incorporation tools etc. The studies which had been conducted on these tools included draft force requirements measurement and soil disturbance characterization resulted due to tool operation (Rahman and Chen [27]), evaluation of existing farming and tillage tools (Chen and Ren [32]), and tool prototype development (Chen [28]). Rahman et al. [33] evaluated the distribution pattern of liquid manure in soil following manure injection. Chen et al. [34] studied the performance of seed drill and crop production as affected by various drill configurations in a soil bin. In general, a soil bin comprises of five major components. These components include; soil container, a carriage, drive system, soil bed preparation device and data collection unit. In case of some soil bins extra components may be added depending on the necessity of the experiment. A camera was added as an additional component for capturing the image of soil movement while a tool cuts through the soil by Jayasuria and Salokhe [22].

The primary function of a soil container is to hold the soil which is to be used for soil-tool interaction study. As discussed by Godwin et al. [23] the carriage rails may also be mounted on a soil container for providing support to the carriage movement. It has also been discussed that the design of a soil container is influenced by the need of testing or experimentation. Depending on this, the soil container can be a moving container or a stationary container. The space limitation is a major factor that influences the overall dimensions of the soil bin. A soil container can be designed to be a combination of small sections for testing various soil types in one test run as put forward by Stafford [24]. Godwin et al. [23] suggested that a soil bin can be designed to have an adjustable width and length to satisfy variety of test purposes. As discussed by Jayasuria and Salokhe [22] some soil containers were designed with transparent sidewalls, for observing the soil displacement within the soil container.

The actual function of a carriage is to transport the test tools. The carriage is also used for transporting soil processing devices and housing instrumentation. Siemens and Waber [25] suggested that a carriage should be designed in such a way that it is rigid enough to avoid distortion due to the weight of test tools and the forces that are produced by the tools. In case of a straight soil bin, appropriate design consideration is necessary for ensuring carriage motion along a straight path. Stafford [24] used an overhead rail for the movement of the carriage. This ensured uniform movement of the carriage along the rails. Godwin et al. [23] made use of a steel angle which served as a guide rail. The wheels were in direct contact of this steel angle and rolled on it instead of on the flat surface of a rail. Another factor associated with carriage design is the tendency for carriage tilting. To avoid such conditions, a separate set of rigid wheels can be used which may run along the bottom surface of an I-beam rail. This can help in avoiding the tilting of the carriage.

The soil processing devices are comprised of the tools which are used to prepare soils and soil bed in the soil container for experimentation. Such devices may be comprised of variety of components. These components can include different soil operation tools such as a rotary tiller, a leveler, a compaction roller etc. These devices can be mounted on a specifically designed carriage for the soil processing devices as discussed by Durant et al. [26]. In order to drive the implement for soil manipulation, a drive system is essential. A typical drive system consists of an electric motor. Stafford [24] used a DC electric motor (20 kW) to drive the carriage which was able to produce a maximum test speed was up to 5.5 m/s. Durant et al. [26] used a hydrostatic transmission system which was driven by an electric motor. A stationary tractor engine of internal combustion type was used by Godwin et al. [23] for driving the carriage.

The force measurement is a most important feature for a soil bin. The most common measurement device used for this purpose is a force dynamometer. The dynamometer can be used to measure forces of the test-tools in horizontal, vertical, and lateral directions (Stafford [24]). Different types of dynamometers can be used for force measurement in soil bin setup. These dynamometers can be classified into two types which are namely; frame types and linkage types. In a frame type dynamometer, force transducers are mounted into a frame that is to be installed between the tool to be tested and a soil bin carriage or a tractor drawbar. This type of dynamometer can measure three orthogonal forces (horizontal or draft, vertical, and lateral) and it has been used for many soil-tool interaction studies (Rahman and Chen [27]; Chen [28]). The frame type dynamometer is normally large in size and thus can result in change of position of the tool relative to the toolbar, which is not

desired in drawbar force measurements. A linkage type dynamometer is more compact in size. Zoerb et al. [29] replaced the usual implement hitch pin with instrumented hitch pins. The force signals were generated with help of strain gauges installed in the pins and these were recorded as the drawbar force of an implement. Most of the pin type dynamometers work along a single axis and thus can measure only draft force. A linkage type ring dynamometers in form of extended octagonal ring (EOR)(Siemens and Weber [25]; Hoag and Yoerger [30]; Godwin [31]) were developed for accommodating large bending moments and measuring two or three forces.

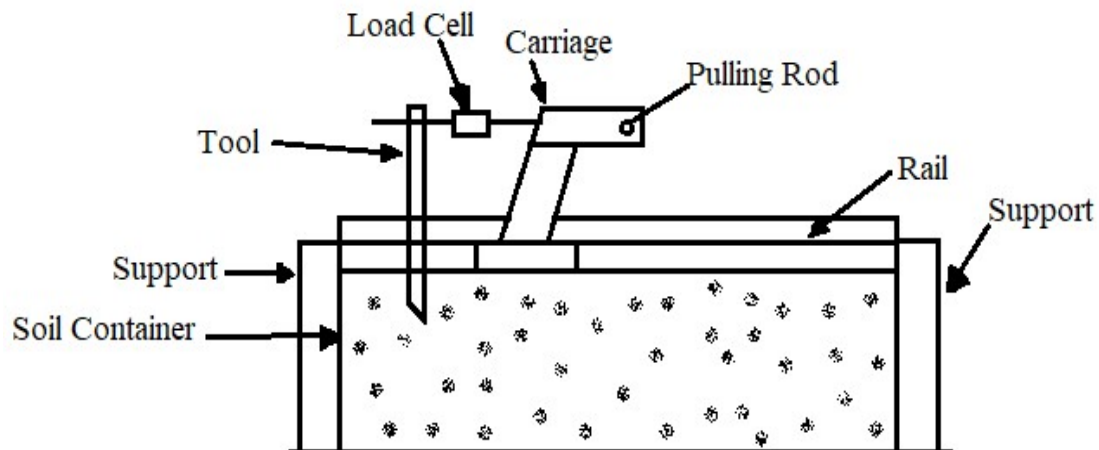


Figure 1: Conceptual sketch of the soil bin

3. Considerations for soil bin design

The development process of a soil bin starts with proper understanding of the parameters to be controlled, parameters to be measured and various constraints on the design. The availability of space is a measure constraint which has to be considered while designing the soil bin. Another important constraint is the maximum speed at which the implement can be tested. The soil bin designed was targeted to be a scaled down model of an actual soil bin setup. The intention behind use of scaled down model was to reduce power fraction required and effectively analyze the soil bin setup and also the variation of draft force with respect to the variation in operation parameters.

In this work, an indoor soil bin was designed. For ease of handling, the maximum dimension of the soil bin was maintained about 0.5 m. This enabled easier transport of bin but forced some restrictions on the speed of operation. The moving part for soil tool interaction was the carriage in this work. This helped in reduction of efforts as the weight of carriage was much lower than the weight of soil container filled with soil. Because of the smaller size of the soil bin, a manual drive was used instead of an electric drive. The load cell of capacity 20 kg was used for measurement of the draft force.

A rectangular shape container is an ideal design for straight soil bins. In this study, the shape of the soil container was kept square so as to allow multiple passes of tool at different locations of the soil bin for ensuring effective measurement of the force. The soil container covered the entire length of carriage movement so as to accommodate a larger range of operating speeds. The guide rails along with the carriage were mounted on top of the soil container with help of supporting plates. The carriage structure was mounted on the guide rails and was free to move along the complete length of the guide rails.

4. Development of Soil Bin Setup

A conceptual sketch was developed for showing the major components of the soil bin. This sketch also included the connections of the various components of the soil bin with each other. The soil container was the base for the entire soil bin. The removable top frame was assembled on top of the soil container. This frame contained the guide rails for the carriage movement with respect to the soil container. The soil bin assembly was done by means of the frame prepared with the slotted angular

plates fixed with one another. The pulling handle used for applying the force was used for holding the sliders of the carriage in straight line and ensuring a straight line motion of the carriage. The load cell was also installed on the horizontal pulling rod and the implement was attached to the other end of the load cell. The detailed sketch is as shown in the figure 1. The CAD model developed with reference to conceptual model is shown in figure 2.

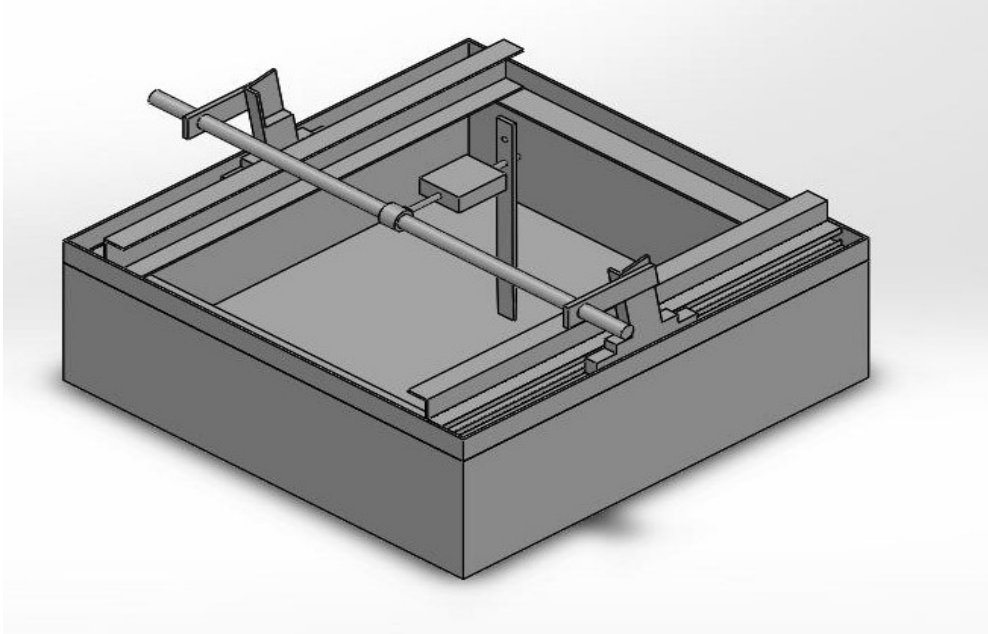


Figure 2: CAD model of the soil bin



Figure 3: Soil bin setup

With reference to this model the actual soil bin was prepared. The soil container was manufactured with galvanized iron sheet. The soil container was of square form having length 51 cm and breadth 51 cm. The depth of soil container was 16 cm. The inner layer of container was covered with plastic sheet for avoiding rusting and easy loading and unloading of soil. The frame was also of a square shape having 'L-shape' cross section. The guide rails were an integrated part of frame running along two

parallel sides of the frame. The sliders were installed on separate guiding rails and a common rod held both of them together by means of threaded joints. This ensured straight line movement of both sliders and avoided any relative motion between them. The sliders along with the connecting rod formed the carriage on which the tool was mounted. The load cell was attached to the connecting rod by means of a customized stud.

The whole frame section along with the carriage and the soil container were assembled together with help of an outer frame of slotted angles was used. This frame rigidly held the soil container and the frame together. The soil layer of height 13 cm was maintained in the soil container. The depth of cut was adjusted by means of different attachment locations available on the tool itself. This ensured the depth of cut remained same till the tool was removed and reinstalled on stud at different attachment location. Final assembly of the soil bin model is shown in figure 3.

The experimentation was carried out involved three parameters associated with draft force. These three parameters were soil moisture level, tillage depth and operation speed. These parameters were chosen with reference to the literature discussed in earlier chapter. The soil moisture level was measured volumetrically by adding specific amount of water to the soil. The tillage depth was measured by means of pre-adjusted tool position while assembling the tool to the load cell. The operation speed was evaluated by measuring the distance travelled by the tool and the time required for the travel. The ratio of travel distance to the time required provide the average speed at which the operation was performed. The draft force was measured with help of the load cell. A weight meter was used along with the load cell for displaying the value of the draft force. The weight meter was a commercially available model in market. This meter had a 'Tare' function which was used for 'Zero Adjustment' of the meter.

5. Observations and Discussion

The soil bin setup developed in this work was used for study of soil tool interaction for a straight face plow having cutting width of 2 cm. The experiments were carried out by varying soil moisture level and tillage depth. For a set soil moisture level and tillage depth, minimum of 5 sets of observations were recorded by varying the operation speed. Total 46 observations were recorded. These observations for the experiment conducted are as shown in table 1.

The soil bin setup developed in this work was used to study the draft force variation with reference to the soil moisture level, tillage depth and operation speed. Following issues were faced while performing experiments with developed soil bin setup.

- The carriage was capable of operating at the maximum speed of 2 km/hr i.e. approximately 55 cm/sec due to the size of the soil container and the frame.
- The carriage motion was not always uniform due to the non-automated carriage drive.
- The soil was loosely compacted for ensuring uniform moisture level across all parts of the soil bin.

Along with these issues, there were some challenges which were faced due to limitations of the instruments used. These challenges are as below.

- The operation speed was not a controlled variable as the carriage movement was powered manually.
- The force meter reading was difficult to observe as the weight meter used had no function for storing maximum force value and the reading was continuously varying with respect to the carriage motion.

It was also observed that the soil bin setup developed in this work was able to measure the draft force for a soil tool interaction study. The data obtained from the experiments mapped the variation in draft force value with the variations in values of various parameters related to soil tool interaction. The further analysis was carried out by plotting draft force against two parameters while keeping third parameter constant. Six such graphs were plotted for which one of the value for either soil moisture level or tillage depth was considered as constant parameter while other parameter out of these was used as one of the independent variables. The second independent variable was operation speed. Third dependent variable was draft force. These graphs are shown in figures 4 to 9. These graphs show that

the draft force increases with increase in operation speed and tillage depth whereas the draft force decreases with increase in soil moisture level.

Table 1. Observations for the experiments conducted with help of soil bin setup

Sr. No.	Soil Moisture (%)	Implement width (m)	Tillage Depth (cm)	Operation Speed (km/hr)	Force Value (N)
1	4.17	0.02	3	0.54	5.32
2	4.17	0.02	3	0.61	5.2
3	4.17	0.02	3	0.46	4.14
4	4.17	0.02	3	0.79	6.27
5	4.17	0.02	3	1.57	7.04
6	4.17	0.02	4	0.87	8.61
7	4.17	0.02	4	0.44	7.84
8	4.17	0.02	4	0.64	8.13
9	4.17	0.02	4	1.17	9.76
10	4.17	0.02	4	0.33	3.99
11	4.17	0.02	5	1.11	10.86
12	4.17	0.02	5	0.37	8.59
13	4.17	0.02	5	0.34	8.37
14	4.17	0.02	5	0.52	9.14
15	4.17	0.02	5	1.17	11.28
16	4.17	0.02	5	0.23	6.81
17	12.5	0.02	3	0.73	7.49
18	12.5	0.02	3	0.65	5.97
19	12.5	0.02	3	0.5	4.01
20	12.5	0.02	3	0.26	2.72
21	12.5	0.02	3	0.49	3.64
22	12.5	0.02	4	1.24	8.96
23	12.5	0.02	4	0.65	5.14
24	12.5	0.02	4	0.52	4.26
25	12.5	0.02	4	0.34	3.78
26	12.5	0.02	4	0.39	4.58
27	12.5	0.02	5	1.1	9.8
28	12.5	0.02	5	0.53	7.34
29	12.5	0.02	5	0.42	6.74
30	12.5	0.02	5	0.45	7.47
31	12.5	0.02	5	0.52	7.26
32	20.83	0.02	3	0.82	6.98
33	20.83	0.02	3	0.39	3.4
34	20.83	0.02	3	0.54	5.29
35	20.83	0.02	3	0.56	5.47
36	20.83	0.02	3	0.56	4.99
37	20.83	0.02	4	0.99	5.99
38	20.83	0.02	4	0.69	4.04
39	20.83	0.02	4	1.25	6.67
40	20.83	0.02	4	1.42	7.25
41	20.83	0.02	4	0.63	3.3
42	20.83	0.02	5	1.55	13.8
43	20.83	0.02	5	0.91	8.18
44	20.83	0.02	5	0.65	4.65
45	20.83	0.02	5	0.53	4.68
46	20.83	0.02	5	0.91	10.28

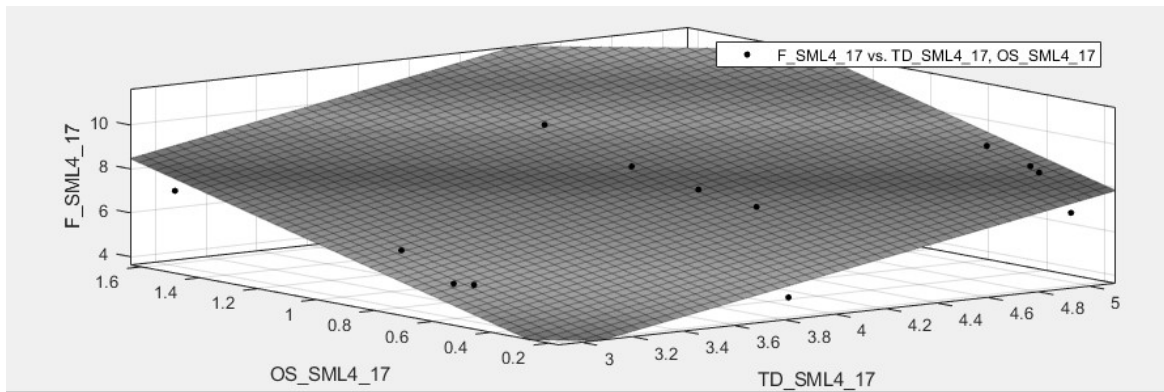


Figure 4. Variation of Draft force with tillage depth and operation speed for soil moisture level 4.17%

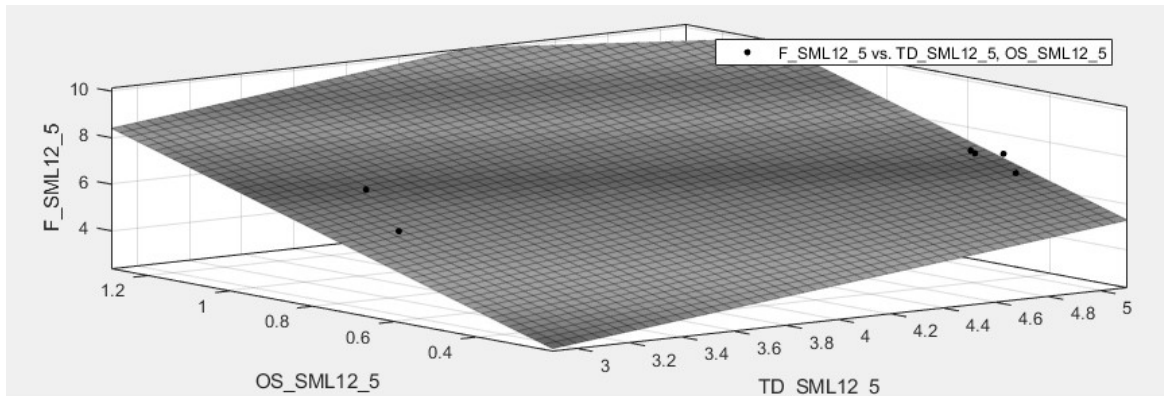


Figure 5. Variation of Draft force with tillage depth and operation speed for soil moisture level 12.5%

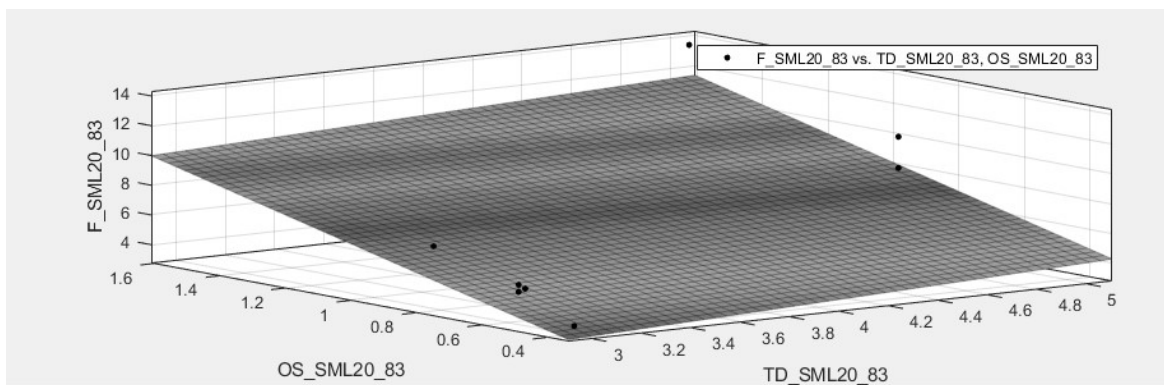


Figure 6. Variation of Draft force with tillage depth and operation speed for soil moisture level 20.83%

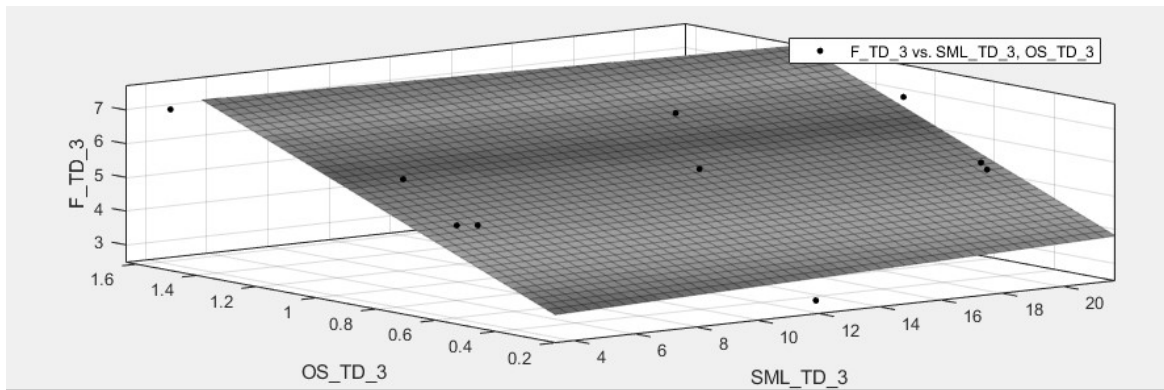


Figure 7. Variation of Draft force with soil moisture percentage and operation speed for tillage depth 3 cm

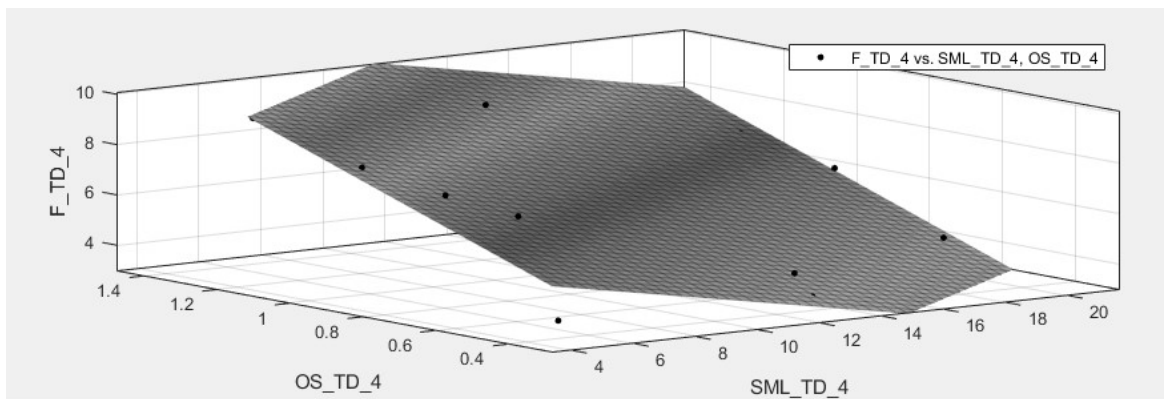


Figure 8. Variation of Draft force with soil moisture percentage and operation speed for tillage depth 4 cm

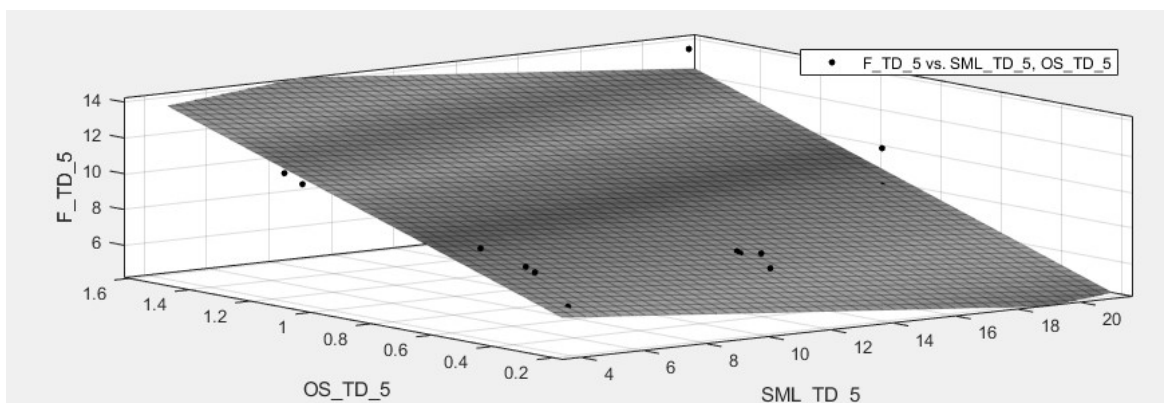


Figure 9. Variation of Draft force with soil moisture percentage and operation speed for tillage depth 5 cm

6. Conclusion

The experimentation showed that the draft force value increased with increase in tillage depth and operation speed. Also the draft force was observed to decrease with increase in soil moisture level. Thus parameter Tillage Depth and Operation Speed were found to be directly proportional to Draft Force parameter and parameter Soil Moisture Level was found to have inverse proportionality with Draft Force. These results were matched with the results obtained by other researchers.

These conclusions matched with the information regarding draft force variation obtained from literature. Yahya et al. (2004) [3] found draft force required was found to increase with increase in both operation speed and tillage depth. Sahu and Raheman (2006) [4] observed that the draft force increased with increase in operation speed and tillage depth. Karmakar et al (2009) [6] found that the draft force increased with increase in forward speed and tillage depth. Naderloo et al. (2009) [7] observed that increase in both speed and depth contributed to increase in draft force value. Al-Suhaibani and Ghaly (2010) [8] showed that increase in plowing depth and forward speed increases draft force. Al-Suhaibani and Ghaly (2013) [9] discussed that the draft force value was found to increase with increase in forward speed and tillage depth for all the three implements. Ji et al. (2014) [14] found that soil moisture content had inverse relation while tillage depth had direct relation with draft force. Mohammadi et al. (2014) [15] observed that draft force value increased with increase in the working depth. Mari et al. (2015) [17] concluded that the soil shear strength decreased with increase in soil moisture level. Deshpande et al. (2015) [18] observed the effect of forward speed to be directly proportional to draft force. Ranjbarian et al. (2017) [16] found that increase in forward velocity results in increase of implement draft. Thus the method implemented for draft force measurement was found to be valid and applicable in actual soil bin model. This type of soil bin study will thus be useful for effectively understanding the farm specific requirements of tillage power and thereby provide a viable support for farmer in overall farm management.

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