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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT OF A SIMPLE, MOVABLE, INDOOR SOIL BIN EQUIPPED WITH SOME NOVEL MEASURING AND SOIL PREPARATION DEVICES

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ABSTRACT

Challenged by the complexities involved in constructing a standard indoor soil bin, and the difficulties in taking certain measurements before, during and after soil bin experiments, a simple soil bin was developed. The soil bin was mainly made with wooden slabs and angle irons. it was equipped with a digitized, mechanically operated cone penetrometer, a sinkage measurement system as well as a stepless soil leveler. An existing manually operated ASABE standard penetrometer was digitized using strain gauges fixed on the penetrometer ring for force measurements and a distance meter for concurrent depth measurement. The penetrometer was operated by a 90 W linear motor with a switch located outside the soil bin thereby making it possible to measure cone index at constant speed in a perfectly vertical direction. The calibration of the strain gauges and the distance meter showed good linearity (R^2>0.997). A stepless levelling device that allows for seamless vertical adjustment of soil height was developed. Soil surfaces levelled with this device had an average coefficient of variation of 0.040 compared with that of 0.080 achieved from carefully manually levelled soil beds. Soil compaction and compaction uniformity experiment was done using sandy clay loam soil which was compacted with a 27 cm diameter steel roller weighing 103 kg/m. Two ultrasonic range finders mounted at the front and rear of the compactor cart automatically measured the sinkage of the soil surface after the compaction. The sinkage on the soil surface and the uniformity in cone index were significantly affected by the number of layers and roller passages and compaction uniformity increases with increase in the number of soil layers. Therefore, the accuracy of the measuring systems and the structural stability of the various components of the soil bin indicate that they are suitable for experiments.

1 Introduction

1.1 Importance of Soil Bin

As important as soil bins are in soil-machine interaction studies (Ani et al., 2018), they could be an expensive and complex structure to acquire and maintain by many laboratories. Many of the ones in existence are somewhat permanent structures which cannot be easily moved from one place to another should the need arise. They are usually rigidly fixed so as not to compromise their structural integrity and to protect them from failure resulting from the enormous forces they are meant to withstand (Ani et al., 2018). Many of the existing soil bins are concrete or steel structures (Godwin et al., 1980; Ademosun, 2014; Ani et al., 2018) whose construction in most cases require high level specialists.

1.2 Previous Experiments Involving Soil Bins

Previously, soil bins have been used for a very wide range of soil-machine interaction researches such as performance evaluation of tillage implements (Endrerud, 1999; Shoji, 2001; Bianchini and Magalhães, 2008; Upadhyay and Raheman, 2018), determining and modelling the energy requirements of soil engaging tools (Shoji, 2004; SeyedReza, 2006; Roul et al., 2009; Subrata et al., 2014; Ibrahmi et al., 2015; Anpat and Raheman, 2017; Upadhyay and Raheman, 2019), soil compaction and cone index tests and modelling (Hernanz et al., 2000; Canillas and Salokhe, 2002; Çarman, 2002; Antille et al., 2013; González Cueto et al., 2013; Lin et al., 2014; Pillinger et al., 2018), traction tests and wheel evaluation of off-road vehicles (Çarman, 2002; Antille et al., 2013; González Cueto et al., 2013; Taghavifar and Mardani, 2014) and so on. The very numerous research done in soil bins underscores its importance. Simplifying its development could therefore make its acquisition a lot easier especially for soil laboratories without huge funding.

1.3 Instrumentation and Soil Preparation in Soil Bin Experiments

Usually, in soil bin experiments, soils are first processed using leveling blades, pulverization tools and are recompacted to the desired cone index. The cone index of the compacted soil is monitored with cone penetrometer which is inserted into the soil at a recommended speed while the resistive force at varying depths is measured. The recommended penetration speed for cone index measurement is 30 mm/s (ASABE, 2019), but maintaining this rate throughout any experiment has been found to be very difficult (Oh et al., 2019) if not impossible. This variation could therefore be a major source of error in cone index measurements. Also, cone index measurement is particularly difficult in soil bin experiments since the operator is usually outside the soil bin so as not to disturb the soil in the soil bin. Maintaining a posture where the penetrometer is perfectly vertical throughout the measurement is no doubt difficult. The developed soil bin was thus equipped with a digitized, mechanically driven cone penetrometer that can be easily operated with a switch located outside the soil bin. Although digital penetrometers are available for purchase, the cost is still very high. A check on globalgilson.com (2020) shows that the price ranges from $3,500 to as high as $5,000 (N1,350,000 to N1,900,000). This high cost has made such a very important measuring device unavailable in many soil laboratories and most laboratories still use the manually operated penetrometer. Even where the digital penetrometer is available, they are still operated by hand (Taghavifar and Mardani, 2014), thus the problem of penetration rate and posture of the operator still remains. Soil sinkage is also a very common parameter measured in soil bin experiments (Canillas and Salokhe, 2002; Çarman, 2002; Roth and Darr, 2011; González Cueto et al., 2013; Taghavifar and Mardani, 2014) because it is one of the most often used parameters in evaluating levels of soil compaction (Valera et al., 2012). The very common methods of measuring soil sinkage is by using plexiglass plate and a Vernier caliper (Taghavifar and Mardani, 2014) or a profilometer (Çarman, 2002). This process is laborious and could be associated with so many errors. To eradicate these, the soil bin was equipped with a novel soil sinkage measuring system. In addition, soil levelling in soil bins is usually done manually either with a rake or with other stepped mechanical leveling devices. Attaining uniformly levelled surface is therefore difficult especially when a precise soil height is to be achieved. To overcome this, the soil bin was also equipped with a stepless leveler that allows for seamless vertical adjustment of soil height.

1.4 Objectives

The objective of this work was to develop a simple and movable but rigid soil bin equipped with digitized, mechanically operated cone penetrometer, new sinkage measurement system and a stepless soil leveler and to evaluate the performances of the newly developed devices and measuring systems.

2. Materials and Methods

2.1 Description of the Soil Bin

A pictorial view of the Soil bin showing some component parts is shown in Figure 1. The soil bin which measured (7 m long, 0.9 m wide and 0.45 m deep) was made of 30mm thick wood. Mild steel angle iron, 5 mm x 5 mm was fixed on both ends of the wood. Another angle iron of the same size was placed on the upper angle iron to serve as the rail. Wood was selected as

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the wall of the soil bin because of its relative advantages in terms of cost, weight, ease of working as well as its fair compressive strength. Perforated angle irons were used as the support between the upper and lower angle irons to reduce the load bored by the wood. Two triangular supports were attached to each side of the soil bin to prevent it from buckling. These triangular supports were bolted to the ground using concrete bolts thereby making the entire structure rigidly fixed. To move the soil bin, the triangular supports would only need to be removed and the soil bin would become movable without necessarily having to dismantle or destroy it which is a common feature of most of the existing immovable soil bins. Two carts (each with four wheels) were put on the rail of the soil bin. One for mounting the soil engaging tools and the other for instrumentation.

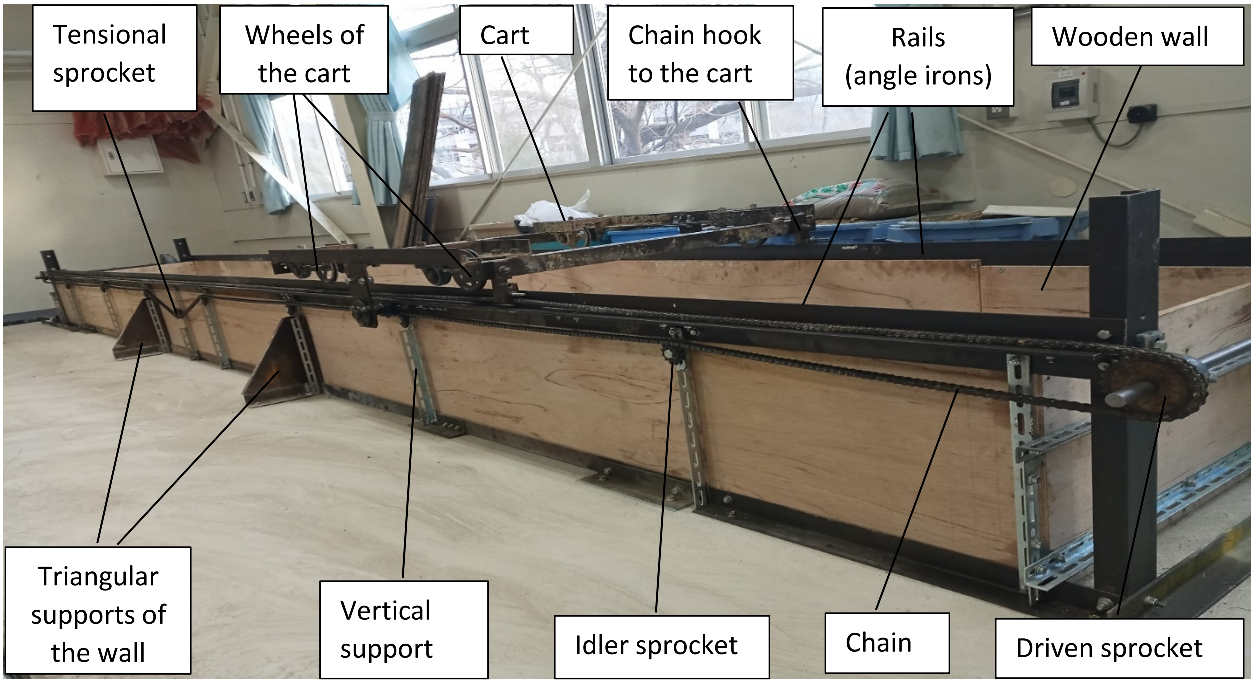

Figure 1: Pictorial view of the soil bin

2.2 Description of the Power and Control Unit of the Soil Bin

The power and control unit of the soil bin is shown in Figure 2. A 2.2 kW-three-phase electric motor was used to power the soil bin. The electric motor was directly connected to a ring cone mechanical variable speed drive (Kopp 29177, Asahi – Seiki Mfg. Co. Ltd., Japan) ranging from 500 rpm to 4500 rpm. A bevel gear box was used to convert the direction of motion and was also used to control the speed of the soil bin cart. A double chain system was used to connect the bevel gear box and the main shaft. Two sprockets were attached to the extreme end of the main shaft and chains were connected to both sides of the cart for stability. The upper part of the chains could freely move on the flat side of the upper angle iron while the lower part was supported by eight freely moving sprockets on each side of the bin to prevent excessive sagging. One of the lower sprockets was used for tension as shown in Figure 1. Electrically operated disc brake and clutch type brake were fixed on the main shaft and between the electric motor and the bevel gear box, respectively. These brakes could be automatically activated by either of the two limit switches (ZL-44A13, Omron, Kyoto) which were fixed on both ends of the soil bin to ensure the carts do not move outside the edges of the rails. A two-stage stepped pulleys and the ring cone of the motor were used to select varying lateral speed of the soil bin cart. A stopwatch was used to measure the lateral safe speed limits of the cart and it ranged from 0.037 m/s to as fast as 2 m/s.

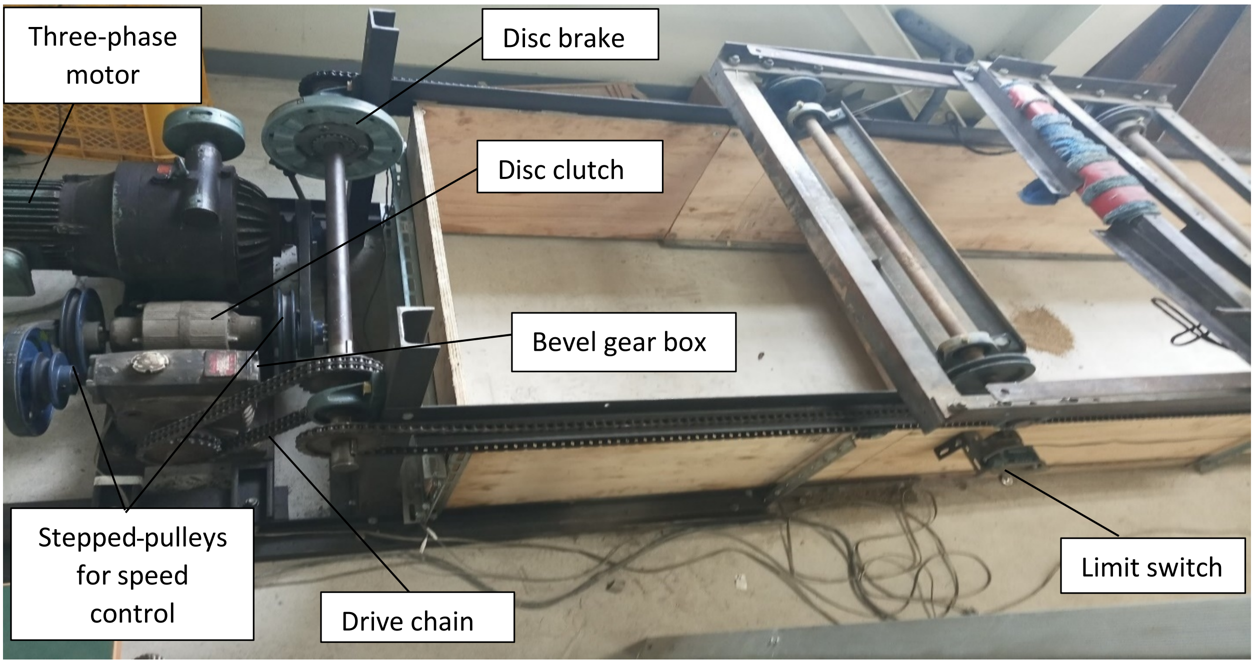

Figure 2: Control and power unit of the soil bin

2.3 Description of the Stepless Soil Leveler and Soil Levelling Test

A stepless leveler was fabricated as shown in Figure 3. The leveling blade was attached to two threaded shafts of 20 mm in diameter. The threaded shafts were inserted into nuts rigidly fixed on the upper part of the cart. A levelling blade, 880 mm by 150 mm made of 3mm gauge aluminum plate was fixed on the lower end of both shafts. The two threaded shafts were connected by means of chain and sprockets to ensure uniform turning. Handles were attached on both shafts for easy turning from either end. The position of the shafts at the point where the leveling blade was on the ground was marked and it coincided with a reference point. When the handle is turned clockwise, the shafts move upwards with the attached levelling blade. The distance between the marked point and the reference point is equal to the distance between the lower part of the levelling blade and the ground. To ensure that the levelling blade does not handle too much soil at one path, the soil was first manually raked and levelled roughly along the height rulers indicated at the side walls of the soil bin before the stepless leveler was used to attain uniformity. A 10 cm deep soil already evenly levelled using the stepless leveler is also shown in Figure 3.

To evaluate the accuracy of the stepless leveler, levelling was done at different speeds of the soil bin and at different soil moisture contents using sandy loam soil and sandy clay soil. Details of the two types of soil, are shown in Table 1. The leveled soil was monitored with one of the ultrasonic range finders (UD-320, Keyence, Osaka). The levelling uniformity was measured by calculating the coefficient of variation (CV) of 100 measurements of the vertical distance between the levelled surface and the surface of the ultrasonic range finder as

$$CV = \frac{\sigma}{\mu} \tag{1}$$

where σ is standard deviation and μ is mean.

Using the stepless leveler, eight experiments were done (2 soils × 2 speeds × 2 moisture contents). The manual levelling was carefully done with a rake. Since the speed of manual levelling could not be varied, only the soil type and moisture content were varied at two levels each (Table 1), resulting in four experiments. The results of the coefficient of variation were statistically analyzed using Stata SE 16 to determine whether the varied parameters have any effect on the levelling uniformity.

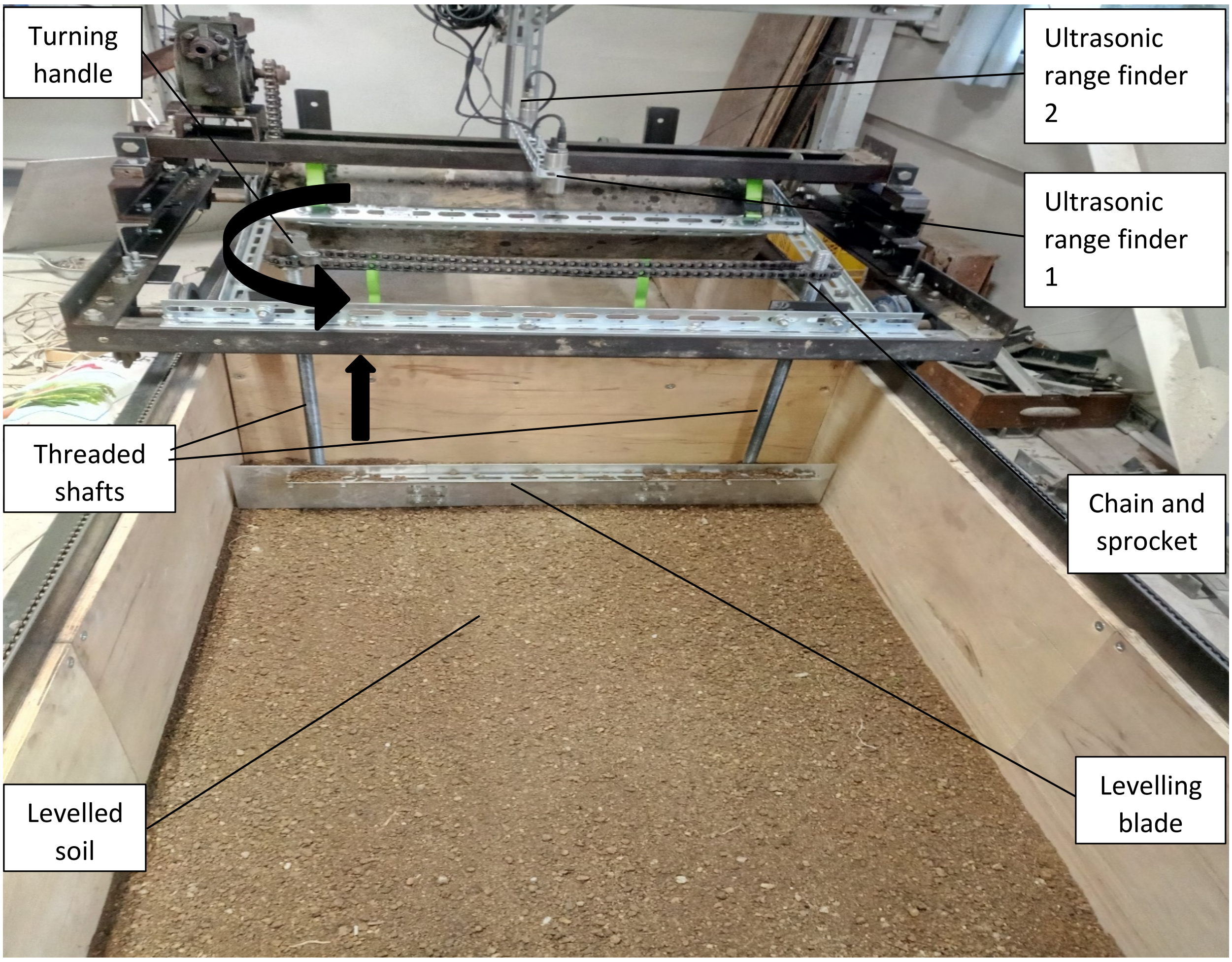

Figure 3: An already levelled soil and the stepless leveler fixed on one of the carts

Table 1: Experimental parameters for soil leveling test

Levelling	Soil type	Leveling speed	Moisture content (d.b.)
Stepless leveler	Sandy loam	0.037 m/s	Dry (5-7%)
Manual levelling	Sandy clay loam	0.140 m/s	Moist (10-12%)

2.4 Description of the Digitized Cone Penetrometer

An ASABE standard penetrometer was rigidly fixed on a linear motor head (Specifications shown in Table 2). The motor was fixed at the center of a beam rigidly fixed over the soil bin cart as shown in Figure 5. Strain gauges (KFGS-2-120-C1-11L1M2R, Kyowa Electronic Instruments, Osaka, Japan) were attached to the outer and inner circumferences of the penetrometer ring (Figures 4 and 5), and the output voltage was amplified and recorded by a data logger (DR-C1MK2, TEAC Corp., Tokyo, Japan). The circuit diagram for the strain gauges connection is shown in Figure 4 . Also, a distance meter (WPS-7500-MK120-CR-U, Micro-Epsilon, Germany) was rigidly fixed close to the linear motor and one end of its wire was fixed on the connector between the motor shaft and the penetrometer as shown in Figure 5. When the penetrometer is moved downward, the wire of the distance meter is pulled, and the corresponding output voltage is linearly generated. These output voltages were also recorded in the same data logger. Therefore, during each measurement, the cone index and the depth were thus simultaneously measured.

Table 2: Specifications of the linear head and the motor used

Items	Specifications
Manufacturer	Oriental Motor, Tokyo, Japan
Model Numbers (MOTOR/LINEAR HEAD)	MSM590-511C/3LF20U-4
Rotational Speed Range	90-1700 RPM
Linear Speed Range	0.15-32 mm/s
Rated Power	90 W

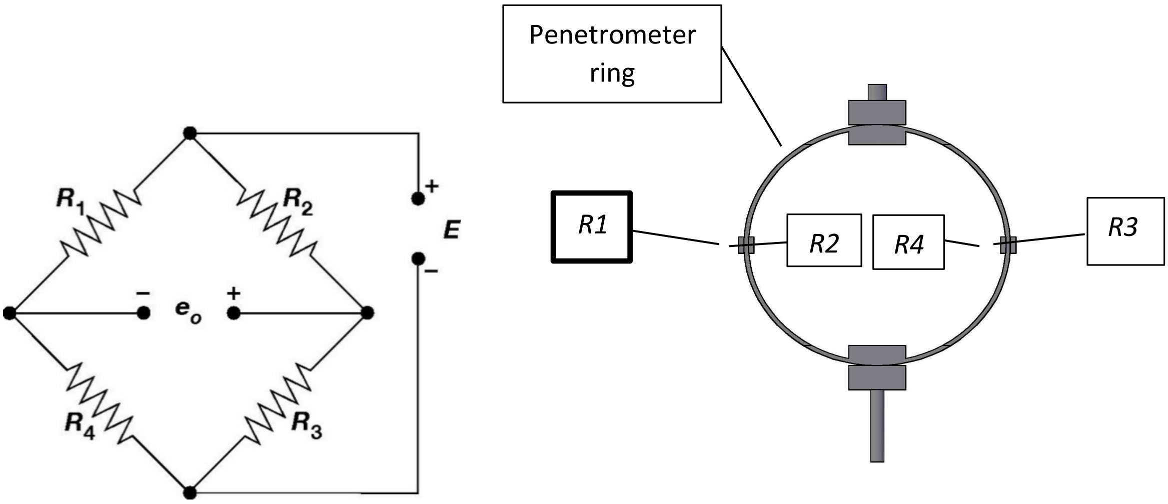

Figure 4: Position of the strain gauges on the penetrometer ring and the circuit diagram for the strain gauges connection

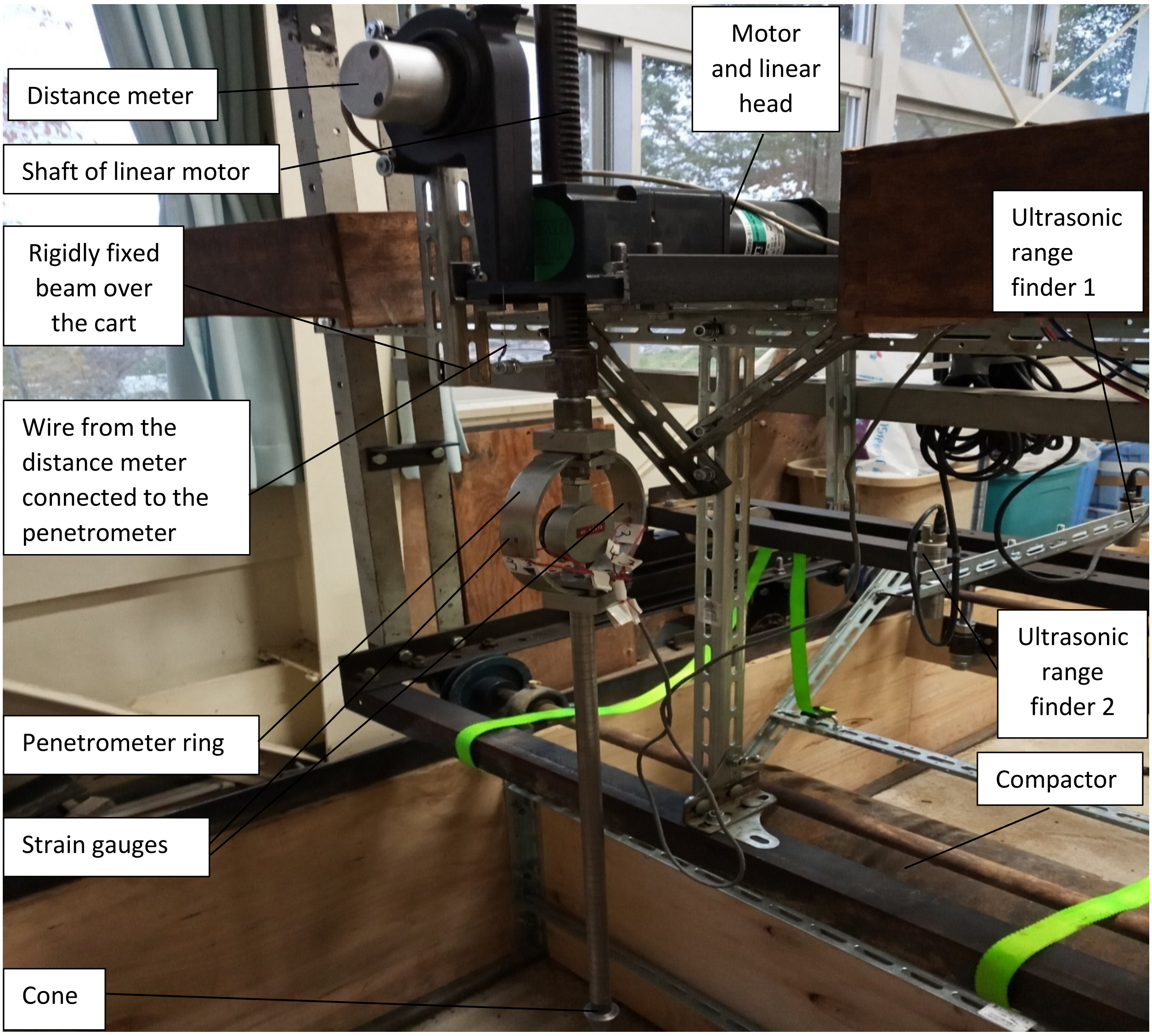

Figure 5: Pictorial diagram showing the digitized penetrometer and other components.

2.5 Soil Compaction and Compaction Uniformity Test

Thirty centimeter (30 cm) deep carefully loosened sandy clayey loam soil was spread in the bin either at once (1-layer Experiment), twice (2-layer experiment, 15 cm each) or four times (4-layer experiment, 7.5 cm each). In the 2- and 4-layer experiments, the next layer of equal depth is carefully laid after the preceding layer had been compacted taking into consideration the sinkage that had occurred. For instance, in a 2-layer experiment, if the height of the first layer had decreased from 15 cm to 12 cm after compaction, the second layer of 15 cm-depth was carefully spread over the compacted layer bringing the total height before compacting the second layer to 27 cm. If after the second layer has been laid and compacted and the soil height decreases to 24 cm, the total sinkage for the experiment is taken to be 6 cm. These precise soil heights were achieved using the developed stepless leveler. The roller used for the compaction was a 27 cm diameter steel pipe weighing 103 kg/m and was rolled on the soil either twice, four times or eight times (defined as the number of passage) at a constant speed of 0.14 m/s. The dependent variables measured after each run of the experiment were cone index and sinkage. The experimental design used was a 3 × 3 full factorial arrangement as shown in Table 3 with two replicates. The resulting cone index and sinkage were statistically analyzed using Stata SE 16.

Table 3: Experimental parameters for compaction uniformity test

Soil type	Number of layers	Number of passages
Sandy clay loam	1	2
	2	4
	4	8

2.6 Sinkage Measuring System

The very common method of measuring sinkage is by using plexiglass plate and a Vernier caliper (Taghavifar and Mardani, 2014) or a profilometer (Çarman, 2002). This process is laborious and could be associated with some errors. To avoid this, two ultrasonic range finders (UD 320, Keyence, Osaka) were placed before and after the roller. The measurements from both ultrasonic range finders were simultaneously logged into the data logger and the sinkage was calculated as:

$$S = H_i - H_C \qquad (2),$$

where S is sinkage (mm), Hi is height of soil (mm) before compaction (measured by ultrasonic range finder 1) and Hc is height of soil (mm) after compaction (measured by ultrasonic range finder 2).

2.7 Calibration of the Instruments

The penetrometer was moved downward until it was just in contact with a solid metal. At this point, the reading on the dial gauge of the penetrometer and the output voltage of the strain gauges were both zero. The penetrometer was then moved downward about 10 times stepwise and the readings on the dial gauge and the output voltages of the strain gauges were recorded for each downward movement. Thereafter, a graph of the dial gauge reading (N) was plotted against output voltage of the strain gauge. Similarly, the distance meter and the ultrasonic range finders were calibrated using a vertically adjustable plate which was moved downward to a known height between the surface of the sensor and the plate ten times and the respective output voltages of the ultrasonic range finders were recorded. A graph of the known height of an adjustable plate was plotted against the output voltages of the distance meter and ultrasonic range finders. Table 4 shows the used transducers and their respective regression coefficients (R^2) and standard errors.

Table 4: Transducers and their calibration parameters.

Transducer	Regression coefficient (R^2)	Standard error
Ultrasonic range finder 1	0.996	0.61 mm
Ultrasonic range finder 2	0.997	0.52 mm
Distance Meter	0.999	0.13 mm
Cone Penetration Resistance Meter (Strain gauges circuit)	0.998	0.01 N

3. Results and Discussion

3.1 Soil Levelling Test

Analysis of variance (ANOVA) on the coefficient of variation resulting from the soil levelling test shows that the levelling done with the developed stepless leveler had a significantly (p<0.1%) lower CV (0.041) compared with (0.080) attained from the levelling done manually as shown in Table 5. This implies that the stepless leveler achieved a more uniformly leveled soil than when it was carefully manually leveled. Also, the soil type significantly affected the CV. Sandy loam had a slightly lower CV than sandy clay loam, which implies that sandy soil was more easily levelled than the soil containing more clay that was likely to result in soil clods. Levelling speed and moisture content did not significantly affect CV at 5% significance level. However, a careful examination of the data shows that there is a trend where mean CV was slightly higher for wet soil than dry soil. This may be because increase in soil moisture concurrently increases the stickiness of the soil especially when the clay content is high and that may make leveling more difficult. The insignificance of all the studied factors (except the soil type) while using the stepless levelling device could imply that it performed well irrespective of the soil type, soil moisture content and the leveling speed and can therefore be used under any of these circumstances.

Table 5: Effects of the different factors on the mean coefficient of variation at the soil leveling test

Factors	Levels	Means
Levelling method	Stepless Leveler	0.041***
	Manual	0.080
Soil type	Sandy loam	0.059*
	Sandy clay loam	0.062
Moisture content	Dry	0.060
	Moist	0.061
Levelling speed	Slow	0.060
	Fast	0.061

* and *** indicate significant difference at 5% and 0.1% levels, respectively.

3.2 Cone Penetration Resistance at the Compaction Uniformity Test

Figure 6 shows the variations in cone penetration resistance resulting from different number of passages and layers. In 1-layer experiment, the maximum penetration resistance increased from 0 to almost 0.6 MPa after the first two passages of the roller, and two passages of the roller attained an additional increase of about 0.2 MPa while four passages increased the maximum penetration resistance by only about 0.1 MPa. This is similar with the findings of Çarman (2002) and Taghavifar and Mardani (2014) who reported that cone penetration resistance increased significantly more at the first run of a single wheel tester than the second and third passages. As the number of layers increases, the maximum and the average cone penetration resistance increases because the amount of compaction effort increases. In the 1-layer experiments, the maximum cone penetration resistance was observed around 10 cm for 2 passages, 8 cm for 4 passages and 7 cm for 8 passages, respectively. The reduced depth at which the maximum cone penetration resistance occur as the number of passages increases is as a result of a slightly increased soil sinkage. After these maximum points, the cone penetration resistance decreased sharply. This implies that the compaction in the 1-layer experiment was only effective until a depth of about 10 cm. For the 2-layer experiments, two peaks of cone penetration resistance were observed at around 7 cm and 18 cm for 4 and 8 passages, respectively. The situation was however different for 2 passage as the second peak was not so obvious. This may imply that as the number of layers increased from one to two, it is necessary to reduce the number of passages to have a more uniformly compacted soil. The 4-layer experiments corroborate this assertion as the cone penetration resistance for 4 and 8 passages increased with depth but that of 2 passages becomes even more straight than it was in the 2-layer experiments. However, the 4-layer experiments represent a typical untilled soil surface condition where the cone index increases with the depth.

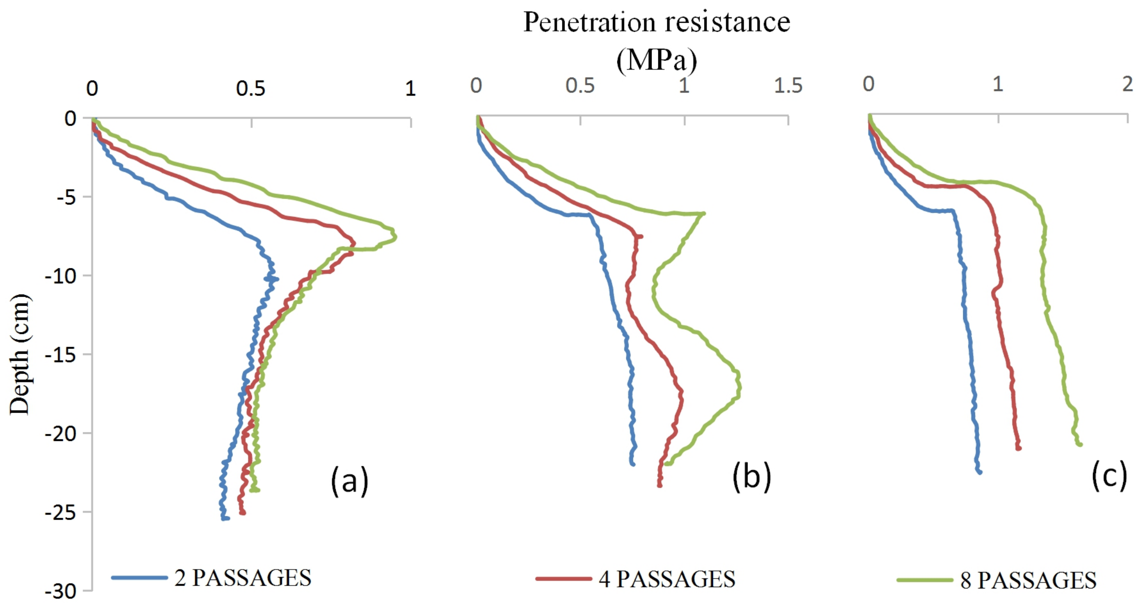

Figure 6: Variations in cone penetration resistance with depth, resulting from different number of layers and passages of the roller: (a) 1-layer, (b) 2-layer and (c) 4-layer experiments

3.3 Effects of Number of Layers and Number of Passages on Compaction Uniformity

A Uniformly compacted soil along its depth has a nearly straight line when the graph of depth versus cone penetration resistance is drawn. For all the experiments, the graphs of 2 passages seem to be relatively the straightest especially below 10 cm depth. This distinction for 2 passages becomes more obvious as the number of layers increases, i.e. 2- and 4-layer experiments when compared with 4 and 8 passages. This could imply that increasing the number of layers and reducing the number of passages could achieve a more uniformly compacted soil, which may be more suitable for soil bin experiments.

3.4 Sinkage

Number of layers as well as number of passages both significantly affected the sinkage at significance levels of 1% and 5% respectively. Table 6 shows that all the three levels of number of layers have resulted in significantly different sinkage. However, 4 and 8 passages are not significantly different from each other. This implies that increasing the number of layers caused more sinkage (compaction) than increasing the number of passages of the roller. This may be because it is easier to compact soil at less volume and that more sinkage occur at the first few passages of the roller as corroborated by Valera et al. (2012) and Taghavifar and Mardani (2014) and the sinkage thereafter does not correspondingly respond to further passage of the roller.

Table 6: Comparison of means for sinkage (mm) for each level of the factors at the compaction uniformity test

Factors	Levels	Mean*
Number of Layers	1	40.7a
	2	63.0b
	4	87.3c
Number of Passes	2	49.5a
	4	64.9b
	8	76.7b

*Means with the same alphabets are not statistically different from each other at 5% significance level.

4. Conclusion

A simple wooden soil bin equipped with a digitized, mechanically operated cone penetrometer, a new sinkage measurement system as well as a new stepless soil leveler was developed. The performance of the developed stepless leveler was satisfactory because its average CV was 0.040 which was considered low when compared with manual levelling. Besides, it made precise vertical adjustment of soil height possible. The digitized penetrometer and the new sinkage measuring system were a lot more convenient than the existing methods of taking these measurements because these measurements were taken only at the press of a switch and without having to enter the soil bin. The results show that soil compaction and sinkage were both significantly affected by the number of soil layers and number of roller passages thereby validating the correctness of the new measuring devices. The results also show that soil compaction is more easily obtained by dividing the soil layer than by increasing the passages of the roller. To achieve a more uniform compaction across the soil depth, increasing the number of layers and reducing the number of roller passages is the best option. The soil bin was adjudged structurally stable since there was no structural failure observed throughout the conduct of the various experiments.

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References

Ademosun, OC. 2014. Soil Tillage Dynamics in Nigeria: Potentials Prospects and Challenges. Proceedings of Nigerian Branch of International Soil Tillage Research Organisation. ISTRO-Nigeria Symposium, Akure 2014. ISN – 978-187-472-4. pp 26-31.

Ani, OA., Uzoejinwa, BB., Ezeama, AO., Onwualu, AP., Ugwu, SN. and Ohagwu, CJ. 2018. Overview of soil-machine interaction studies in soil bins. Soil and Tillage Research, 175: 13-27. doi:https://doi.org/10.1016/j.still.2017.08.002.

Anpat, RM. and Raheman, H. 2017. Investigations on power requirement of active-passive combination tillage implement. Engineering in Agriculture, Environment and Food, 10(1): 4-13. doi:https://doi.org/10.1016/j.eaef.2016.06.004.

Antille, L., Ansorge, D., Dresser, M. and Godwin, JR. 2013. Soil Displacement and Soil Bulk Density Changes as Affected by Tire Size. Transactions of the ASABE, 56(5): 1683-1693. doi:https://doi.org/10.13031/trans.56.9886.

ASABE. 2019. Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. 1.

Bianchini, A. and Magalhães, PSG. 2008. Evaluation of coulters for cutting sugar cane residue in a soil bin. Biosystems Engineering, 100(3): 370-375. doi:https://doi.org/10.1016/j.biosystemseng.2008.04.012.

Canillas, EC. and Salokhe, VM. 2002. Modeling compaction in agricultural soils. Journal of Terramechanics, 39(2): 71-84. doi:https://doi.org/10.1016/S0022-4898(02)00007-1.

Çarman, K. 2002. Compaction characteristics of towed wheels on clay loam in a soil bin. Soil and Tillage Research, 65(1): 37-43. doi:https://doi.org/10.1016/S0167-1987(01)00281-1.

Endrerud, HC. 1999. Dynamic Performance of drill coulters in a soil bin. Journal of Agricultural Engineering Research, 74(4): 391-401. doi:https://doi.org/10.1006/jaer.1999.0477.

Godwin, RJ., Spoor, G. and Kilgour, J. 1980. The design and operation of a simple low cost soil bin. Journal of Agricultural Engineering Research, 25(1): 99-104. doi:https://doi.org/10.1016/0021-8634(80)90051-7.

González Cueto, O., Iglesias Coronel, CE., Recarey Morfa, CA., Urriolagoitia Sosa, G., Hernández Gómez, LH., Urriolagoitia Calderón, G. and Herrera Suárez, M. 2013. Three dimensional finite element model of soil compaction caused by agricultural tire traffic. Computers and Electronics in Agriculture, 99: 146-152. doi:https://doi.org/10.1016/j.compag.2013.08.026.

Hernanz, JL., Peixoto, H., Cerisola, C. and Sánchez-Girón, V. 2000. An empirical model to predict soil bulk density profiles in field conditions using penetration resistance, moisture content and soil depth. Journal of Terramechanics, 37(4): 167-184. doi:https://doi.org/10.1016/S0022-4898(99)00020-8.

Ibrahmi, A., Bentaher, H., Hbaieb, M., Maalej, A. and Mouazen, AM. 2015. Study the effect of tool geometry and operational conditions on mouldboard plough forces and energy requirement: Part 1. Finite element simulation. Computers and Electronics in Agriculture, 117: 258-267. doi:https://doi.org/10.1016/j.compag.2015.08.006.

Lin, J., Sun, Y. and Schulze Lammers, P. 2014. Evaluating model-based relationship of cone index, soil water content and bulk density using dual-sensor penetrometer data. Soil and Tillage Research, 138: 9-16. doi:https://doi.org/10.1016/j.still.2013.12.004.

Oh, J., Nam, J-S., Kim, S. and Park, Y-J. 2019. Influence of tire inflation pressure on the estimation of rating cone index using wheel sinkage. Journal of Terramechanics, 84: 13-20. doi:https://doi.org/10.1016/j.jterra.2019.04.002.

Pillinger, G., Géczy, A., Hudoba, Z. and Kiss, P. 2018. Determination of soil density by cone index data. Journal of Terramechanics, 77: 69-74. doi:https://doi.org/10.1016/j.jterra.2018.03.003.

Roth, J. and Darr, M. 2011. Data acquisition system for soil–tire interface stress measurement. Computers and Electronics in Agriculture, 78(2): 162-166. doi:https://doi.org/10.1016/j.compag.2011.07.003.

Roul, AK., Raheman, H., Pansare, MS. and Machavaram, R. 2009. Predicting the draught requirement of tillage implements in sandy clay loam soil using an artificial neural network. Biosystems Engineering, 104(4): 476-485. doi:https://doi.org/10.1016/j.biosystemseng.2009.09.004.

SeyedReza, A. Z. 2006. Modelling of Energy Requirements by a Narrow Tillage Tool. Ph.D Thesis, University of Saskatchewan, University of Saskatchewan, Canada.

Shoji, K. 2001. Design of a Model 'Spot Plough' for Inversion of the Soil Slice within the Furrow. Journal of Agricultural Engineering Research, 79(3): 283-297. doi:https://doi.org/10.1006/jaer.2000.0700.

Shoji, K. 2004. Forces on a Model 'Spot Plough'. Biosystems Engineering, 87(1): 39-45. doi:https://doi.org/10.1016/j.biosystemseng.2003.10.004.

StataCorp. 2019. Stata Statistical Software: Release 16. College Station, TX: StataCorp LLC.

Subrata, MK., Basudeb, B., Somenath, M. and Karmakar, S. 2014. Soil-Blade Interaction of a Rotary Tiller: Soil Bin Evaluation. International Journal of Sustainable Agricultural Research, 1(3): 58-69.

Taghavifar, H. and Mardani, A. 2014. Effect of velocity, wheel load and multipass on soil compaction. Journal of the Saudi Society of Agricultural Sciences, 13(1): 57-66. doi:https://doi.org/10.1016/j.jssas.2013.01.004.

Upadhyaya, G. and Raheman, H. 2018. Performance of combined offset disc harrow (front active and rear passive set configuration) in soil bin. Journal of Terramechanics, 78: 27-37. doi:https://doi.org/10.1016/j.jterra.2018.04.002.

Upadhyaya, G. and Raheman, H. 2019. Specific draft estimation model for offset disc harrows. Soil and Tillage Research, 191: 75-84. doi:https://doi.org/10.1016/j.still.2019.03.021.

Valera, DL., Gil, J. and Agüera, J. 2012. Design of a new sensor for determination of the effects of tractor field usage in Southern Spain: Soil sinkage and alterations in the cone index and dry bulk density. Sensors, 12(10): 13480-13490. doi:10.3390/s121013480.