Ethiopian Journal of Science and Sustainable Development

e-ISSN 2663-3205 Volume 9(1), 2022

Journal Home Page: www.ejssd.astu.edu.et

EJSSD ETHIOPIAN JOURNAL OF SCIENCE AND SUSTAINABLE DEVELOPMENT

Research Paper

Modelling and Simulation of Hydraulic System to Measure Soil Compaction for Agricultural Field

Yared Seifu[1,*], Someshakher S. Hiremath[2], Simie Tola[1], Amana Wako[1]

[1]*Department of Mechanical System and Vehicle Engineering, Adama Science and Technology University, P.O. Box: 1888, Adama, Ethiopia*

[2]*Department of Mechanical Engineering (Precision and Instrumentation Laboratory Engineering). (IITM) Indian Institute of Technology, Madras University Chennai, India*

Article Info

Article History:
Received 28 August 2021
Received in revised form 11 November 2021
Accepted 12 March 2022

Keywords:
Agricultural field
Hydraulic System
MATLAB
Modelling
Simulation
Soil Compaction

Abstract

Soil compaction is one of the negative factors associated in the top layer of the soil by heavy agricultural machinery in the agricultural field that limits ploughing tool movement, plant growth and crop yield. Soil compaction has been conventionally measured by using a manual operated cone penetrometer which has certain ergonomically restriction tackled by the operator, it takes more time and difficult to obtain compaction data. The study aimed to design and develop a hydraulic system to measure soil compaction for agricultural field, to simulate soil compaction measuring system using MATLAB Simulink 2018 and to analyze the simulation output. The modelling and simulation include the hydraulic system used for actuate the compaction measuring cone penetrometer by considering the vertical force coming from double acting hydraulic cylinder as variable mass and the soil as a stiffness and damping property. From the simulation output, the hydraulic performance based on soil compaction measurement with the parameters such as hydraulic pressure as cone index, depth of operation, hydraulic torque, and power were analyzed. The time required for the cylinder extension to insert the cone penetrometer to the soil was 3.3 seconds with the maximum speed of cylinder extension of 0.3 mm/s. The maximum downward penetration resistance was 0.3 N. The pressure varies from 24 Pa to 38 Pa during extension of the cylinder and 0 to 15 Pa during retraction with the maximum flow rate of 3.8×10^{-6} m^3/s. The relationship between hydraulic power and flow rate is directly proportional. Hydraulic torque and flow rate have inversely proportional relationship.

1. Introduction

Farm mechanization is the main indicator of the modernizing the agricultural and use of farm machines that can replace human and animal power in agricultural processes. Farm machineries are used for land preparation to the harvesting steps by driving in farm land in mechanization system. During field operation, the weight of farm machinery compact the agricultural soil resulting in increase and decrease of soil bulk density and porosity, respectively due to the contact with the tires or tracks of tractors (Ungureanu et al., 2015). Soil compaction is not only caused by farm machinery, but also by livestock trampling (Chyba et al., 2014).

The risk of compaction is also dependent on the soil tillage and crop rotations, soil moisture and working depth. Soil compaction has been continuously disregarded in the management of agricultural traffic, even though it is extremely relevant to maintain the soil

*Corresponding author, e-mail: *yaredseifu80@gmail.com*

https://doi.org/10.20372/ejssdastu:v9.i1.2022.391

quality of different agro ecosystems (Guimaraes et al., 2019). Soil compaction is the major problem that affect the crop production by limiting the potential yield (Scarparea et al., 2019). Top layer of agricultural soil compaction by heavy agricultural machinery is one of the main negative factor which limits plant growth and crop yield (Benevenute et al., 2020). The compacted soil is difficult to plough since its strength and draft resistance is high.

Physical properties of soil play an important role in determining soil's suitability for agricultural, environmental and engineering uses. The supporting capability; movement, retention and availability of water and nutrients to plants; ease in penetration of roots, and flow of heat and air are directly associated with physical properties of the soil (Phogat et al., 2015). Soil strength can be measured traditionally using a hand operated soil cone penetrometer (Guimaraes et al., 2019). Soil cone index is widely used to assess soil strength or soil compaction in tillage research. Hence soil cone penetrometer is an important measuring instrument to determine soil physical properties. Excessive compactness is detrimental to maintain a good root environment. It also reduces penetration of water and increases runoff and erosion (Mudarisov et al., 2020). The forces from agricultural equipment cause soil particles to compact closer and organized into a smaller volume. As soil particles are compressed together, the space between particles (pore space) is reduced, thereby reducing the space available in the soil for air and water.

Kumar et al. (2019) designed and developed hydraulically operated mechanical soil cone penetrometer to measure soil resistance on tillage in the field up to a maximum cone index value of 2000 kPa. Tekin et al. (2007) developed a Hydraulic-driven soil penetrometer for measuring soil compaction in field conditions. Wang et al. (2020) designed on the basis of hydraulic principle, which uses tractor hydraulic system and comprised of driving unit for inserting the probe into the soil at the desired speed. In mechanized farming system, farm machineries are used from land preparation to harvesting by operating in farm land. Throughout the literature survey conducted, in Ethiopian there is no research done so far on hydraulically operated tractor mounted soil compaction measuring system. In field experiment level, Ethiopian soil compaction rate and plant/seed growing relation should be studied for improving the farming system. A hydraulically operated soil compaction measuring system which is mounted on tractor in tillage field has not been studied so far. In global level, many researches were conducted on related areas.

In the development of separate system for measuring soil resistance and soil compaction, almost all researchers were used cone penetrometer. Soil compaction measuring instrument in field work at different soil depth and soil profile is crucial in our country to overcome the aforementioned problems. Therefore, the study aimed to design and develop a hydraulic system to measure soil compaction for agricultural field, to simulate soil compaction measuring system using MATLAB Simulink and to analyze the simulation output. From the simulation output, the hydraulically actuated soil compaction measurement which consists of parameters such as hydraulic pressure as cone index, depth of operation, soil type, hydraulic torque, and power were analyzed.

2. Methodology

The methodology followed in this work is summurized in Figure 1. The work started by assuming standard parameters like maximum cone index value based on agrotechnical requirement. Based on the assumption, the designing of hydraulic components for actuating the soil compaction instrument were done. Then, according to the design, simulation on MATLAB Simulink was done. The final step was discussion of the results based on time require for the extension and retraction of the double acting cylinder for accomplishment of the soil compaction measurement with respect to parameters like pressure difference, flow rate, hydraulic torque, power, etc. This soil testing instrument can be used in all types of soil except stony farm land since the hydraulic power damage the cone penetrometer probe. The simulation input and output parameters are shown in Figure 2. The results and discussion are based on time required for the extension and retraction of the double acting cylinder.

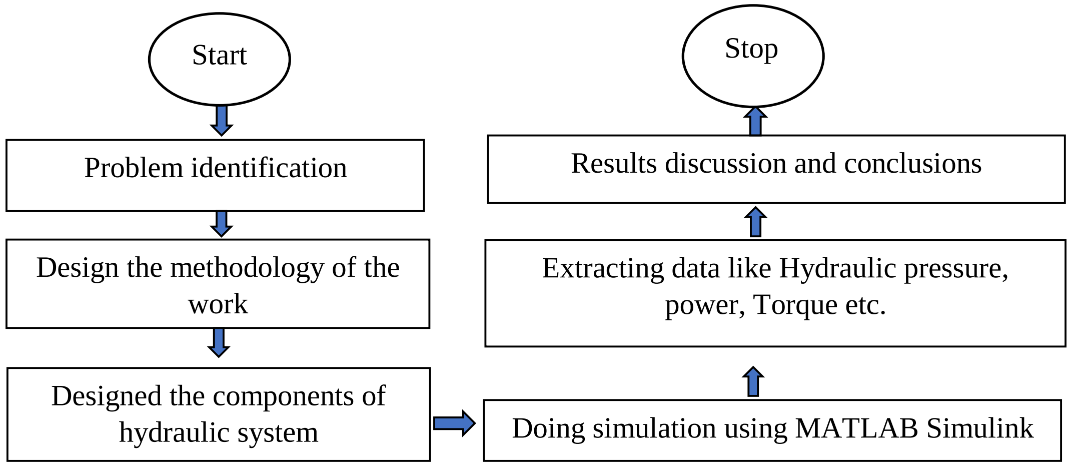

Figure 1: Methodology Flowchart

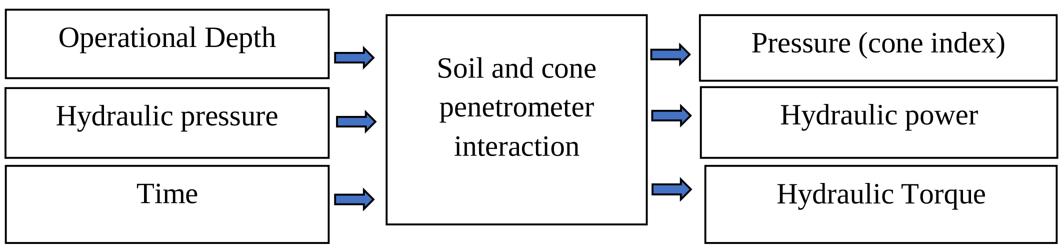

Figure 2: Theoretical frame work of input output parameter

2.1. Operational definition

The system gates hydraulic power from the tractor hydraulic power unit which contains reservoir and pump. The hydraulic fluid passing from pump can be connected to the pressure relief valve for regulating excess pressure. The double acting cylinder movement is controlled by a four port three position directional control valves (4/3DCV). The solid line indicates the path of the fluid as shown in Figure 3 to Figure 5. Initially, in ideal work position, the pump pressure line is connected to the off or to the middle position of 4/3DCV. As shown in Figure 3, the pump pressure doesn't pass to the double acting cylinder so that the fluid return to the tank through the pressure relief valve.

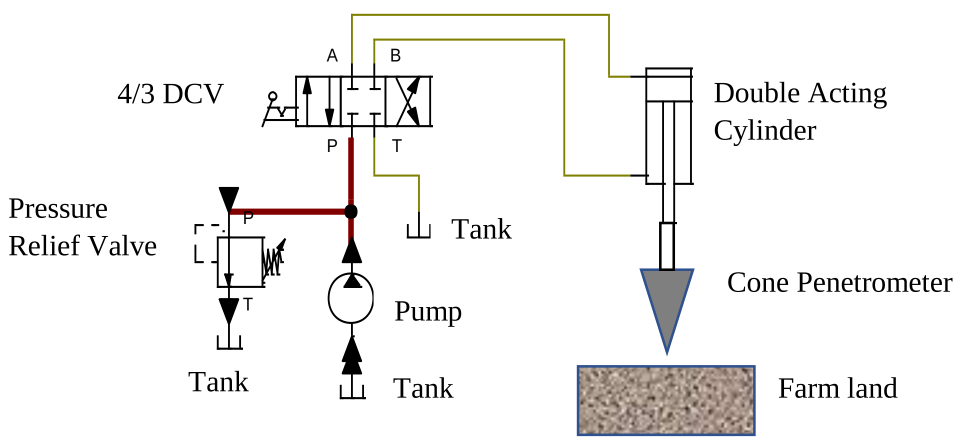

Figure 3: Shutoff position of the hydraulic circuit of the system

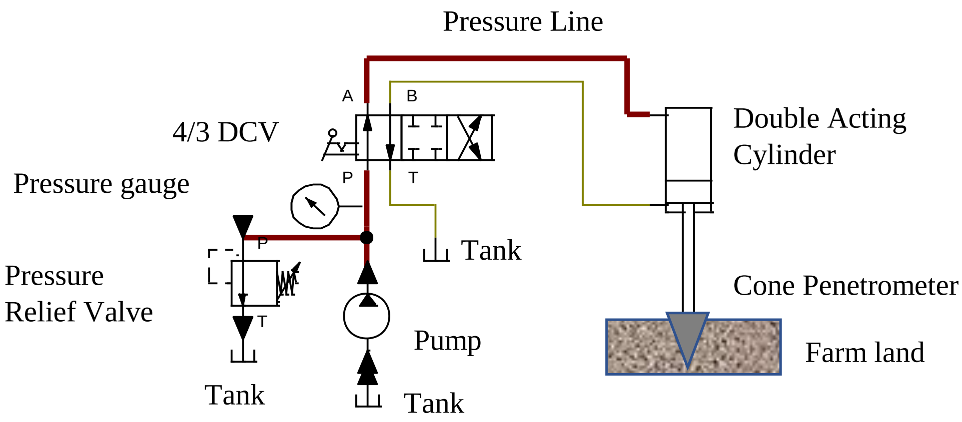

Figure 4: Working position of the hydraulic circuit of the system

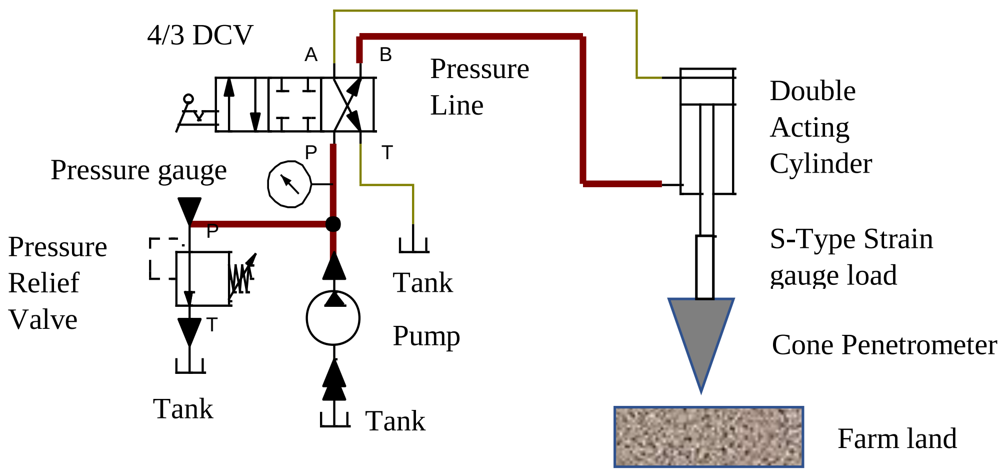

Figure 5: Retract position of the hydraulic circuit of the system

When the 4/3 DCV allow the fluid coming from the tank through pump it extends the cylinder road as shown in Figure 4 and inserts the cone penetrometer into the soil to measure the soil compaction.

The system in Figure 5 shows when the 4/3 DCV allow the fluid coming from the tank through pump and passing at the third position, it retracts the cylinder road and take out the cone penetrometer from the soil.

2.2. Design and Modelling

The designed model of cone penetrometer was done based on force coming from the hydraulic double acting cylinder. The forces model and design acting on the cone penetrometer at static condition are downward hydraulic force and upward soil resistance (Figure 6) are incorporated in design process (Freitag et al., 1970).

Design of Cylinder: Design of hydraulic cylinder is based on the maximum thrust required to insert the penetrometer probe into the soil. The maximum thrust

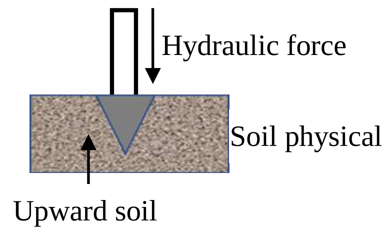

Figure 6: Factors affecting tillage operation

required for the penetrometer can be calculated using Equation 1 (Perumpral, 1987).

$$F = CI \times A \qquad (1)$$

where, F = required thrust, CI = maximum cone index to be measured, and A= base area of cone in case of cone penetrometer.

The maximum cone index of soil for which the system to be designed is assumed to be 3 MPa. American society of Agricultural and Biological engineers (ASABE, 1968) adopted the standardization cone penetrometer as a recommendation for field use and this is still in use today. These are cone of 323 mm^2 base area and 20.27 mm base diameter with a 15.88 mm diameter probe for loose soil and the second one is a cone of 130 mm^2 base area and 12.83 mm base diameter with a 9.53 mm diameter probe for firm soil. Using the first standard, the maximum force required for the penetrometer can be calculated as: Maximum Force (F) = $3\times10^6\times3.23\times10^{-4}$ = 967 N.

The piston rod diameter is checked for buckling by using Euler's formula (Equation 2). So, Euler's strut theory is used to withstand buckling (De Cicco et al., 2022) .

$$d_{(m_i n)} = 4\sqrt{\frac{F \times K^2 L^2 \times 64}{\pi^2 E}} \qquad (2)$$

where, F (buckling load on cylinder rod) = maximum force applied on cylinder rod × 2, E = young's modulus of elasticity (200 GPa for steel EN8), d = diameter of cylinder rod, L = length of cylinder rod (taking 200 mm) and K = constant, 2 for one end fixed and another end free.

$$d_{(m_i n)} = 4\sqrt{\frac{967 \times 2^2 \times 0.2^2 \times 64}{\pi^2 \times 200 \times 10^9}} = 0.008418m = 8.42mm$$

The aavailable size of cylinder rod is 32 mm with cylinder bore of 100 mm. Hence, the cylinder rod is safe for buckling. As a result, Equation 3 can be used to find the smallest diameter of cylinder rod that can withstand the load (De Cicco et al., 2022).

$$d = \sqrt{\frac{4F}{\pi\sigma}} \qquad (3)$$

where, σ is maximum yield stress of cylinder road material (380 MPa) and taking factor of safety = 2

$$d = \sqrt{\frac{4 \times 967 \times 2}{\pi \times 380}} = 6.48mm$$

Available size of cylinder rod is 32 mm. Hence, the cylinder can resist the load.

The pressure required to developed thrust on the annular side of the cylinder can be calculated using Equation 4 (Watton, 2007).

$$P = \frac{F}{A} = \frac{F}{\frac{\pi}{4}(d_c^2 - d_r^2)} \qquad (4)$$

where, P is pressure coming from hydraulic system, d_c and d_r are cylinder diameter and cylinder road diameter, respectively.

$$P = \frac{967}{\frac{\pi}{4}(100^2 - 32^2 d)} = 1.3724\, bar$$

Relief valve pressure should be adjusted at a pressure >25% than that required to give a thrust, considering the pressure drop in the pipes and other components. The bore side and annual side in m^2 of the cylinder are calculated using Equation 5 and 6, respectively (Watton, 2007).

$$\text{Full bore area, } A = \frac{\pi}{4}(d_c^2) \qquad (5)$$

$$A = \frac{\pi}{4}(100^2) = 7854\, mm^2 = 78.54\, cm^2$$

$$\text{Annulus area, } (A - a) = A = \frac{\pi}{4}(d_c^2 - d_r^2) \qquad (6)$$

$$A = \frac{\pi}{4}(100^2 - 32^2) = 7050\, mm^2 = 70.50\, cm^2$$

The piston velocity should be 3 cm/s to penetrate into soil to meet the standard cone penetration velocity as per ASAE S313.3.

When piston rod is extending Piston velocity, V can be calculated using Equation 7 (Mirzaliev et al., 2020):

$$V = \frac{Q_E}{A} = \frac{q_E}{A - a} = 3cm/s = 30mm/s \qquad (7)$$

where, Q_E = flow into full bore end of cylinder when extending in m^3/s, q_E = flow from annulus end of cylinder when extending

$$Q_E = A \times V \qquad (8)$$

$$QE = 78.54 \times 3 = 235.62\, cm^3/s = 0.01414 m^3/min = 14.14 lpm$$

$$q_E = (A - a) \times V \qquad (9)$$

$$q_E = 70.5 \times 3 = 211.5\, cm^3/s = 0.1269 m^3/min = 12.69 lpm$$

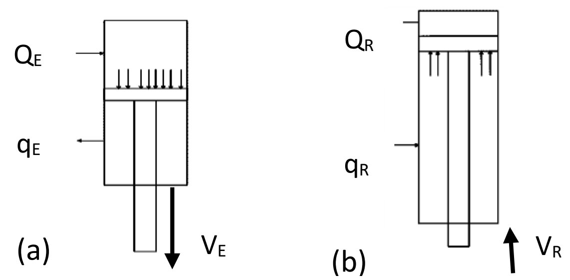

Figure 7: (a) Cylinder under extended condition (b) Cylinder under retracted condition.

When piston rod is retracted, piston velocity, V, can be calculated using Equation 10 (Watton, 2009):

$$V = \frac{Q_R}{A} = \frac{q_R}{A - a} \qquad (10)$$

where, Q_R= flow into full bore end of cylinder when retracting in m^3/s, q_R= flow from annulus end of cylinder when retracting in m^3/s = Q_E =235.62 cm^3/s

$$V = \frac{235.62}{70.5} = 3.34\, m/s$$

$$Q_R = A \times V = 78.54 \times 3.34 = 262.324 cm^3/s$$

$$= 0.01574 m^3/min \;\; = 15.74 lpm$$

Table 1: Design summary for the double acting cylinder

S. No.	Parameters	Value
1	Cylinder diameter	100 mm
2	Rod diameter	32 mm
3	Stroke length	200 mm
4	Stroke speed	30 mm/s
5	Return stroke speed	33.4 mm/s
6	Oil flow required in forward stroke	14.14 lpm
7	Oil flow required in return stroke	15.74 lpm
8	Full bore area	7854 mm^2
9	Annual area	7050 mm^2

2.3. Modeling of the soil compaction measuring system

The MATLAB Simulink of hydraulic system model in Figure 6 includes a tractor auxiliary hydraulic system which includes hydraulic oil, hydraulic pump for crating pressure and velocity, hydraulic motor for creating mechanical rotation. The system get power from the hydraulic reference unit passing through pump. The pressure relief valve used for regulating excess pressure and save the four by three directional pressure control valve. Manual operated four port three position directional control valve directs the directional movement of the fluid as well as stops the operation. The double-acting cylinder create linear movement and inserting cone penetrometer into the soil for measuring the vertical soil pressure.

A real system gates hydraulic power from the tractor hydraulic power unit, which contains a reservoir and pump. The pressure applied from the cylinder is modelled as a variable mass and the soil is modelled as solid particle which contains its own spring and damping property. The model input parameters are the design parameters which are summarized in Table 1.

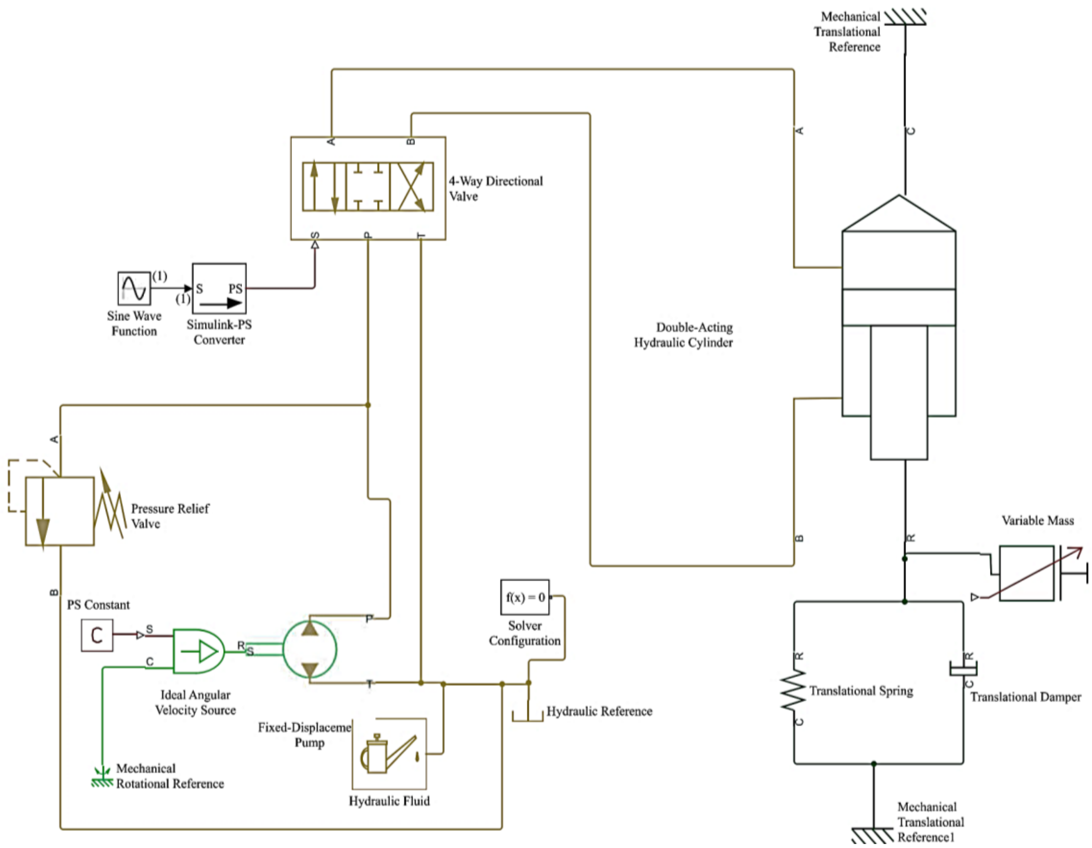

Figure 8: MATLAB Simulink model of the hydraulic system

3. Results and discussion

The results of the hydraulic cylinder simulation outputs which include time required for the cylinder extension and retraction, pressure variation during cylinder extension and retraction, soil compaction resistance in a form of damper and soil stiffness in a form of spring property, the flow rate through pump to hydraulic cylinder, power and torque are presented and discussed in this section. The simulation output graph (Figure 9) represents a double-acting hydraulic cylinder output parameter during the extension of cylinder. The model of the cylinder is constructed from the translational hydro-mechanical converter and translational hard stop blocks. The rod motion is limited with the mechanical translational hard stop block. The time required for the cylinder extension to insert the cone penetrometer to the soil is 3.3 seconds and the maximum speed of cylinder extension is 0.3 mm/s.

The simulation output graph (Figure 10) shows the pressure variation through pressure line and returning line. Connections A and B are hydraulic conserving ports. Port A is connected to converter A and port B is connected to converter B.

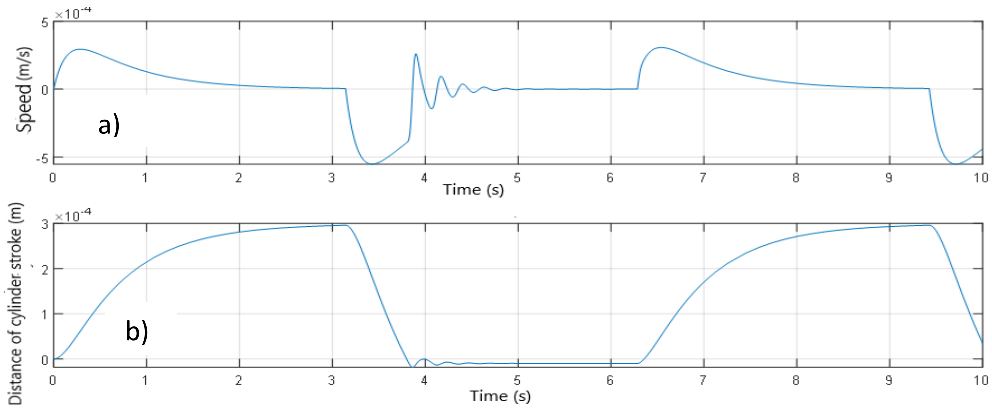

Figure 9: a) hydraulic cylinder speed with respect to simulation time and b) single stroke distance with respect to simulation time

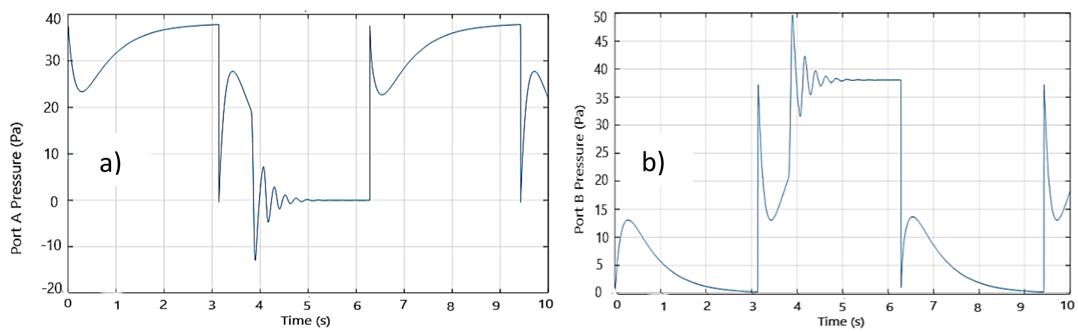

Figure 10: a) pressure variation in hydraulic cylinder at port A with respect to simulation time and b) Port B with respect to simulation time

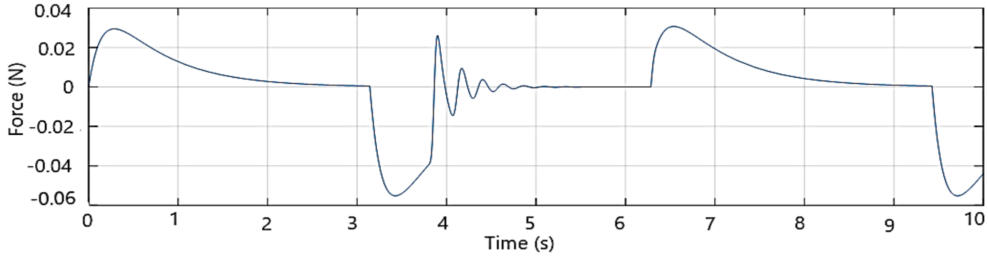

Figure 11: Soil compaction resistance force with respect to simulation time

The block directionality is adjustable and can be controlled with the cylinder orientation parameter. The result shows in the first 3 seconds the pressure in port A varies within 24 Pa to 38 Pa and pressure in port B varies within 0 to 15 Pa.

The graph in Figure 11 shows soil compaction resistance force with respect to simulation time based the model of soil as solid variable mass. The result indicates that the maximum soil resistance force is 0.03 N.

The block in model has one mechanical translational conserving port and one physical signal input representing the soil as mass. The block positive direction is from its port to the reference point. This means that the inertia force is positive if mass is accelerated in positive direction. Based on this, the graph output in Figure 12 shows the maximum downward penetration resistance force of 0.3 N with the maximum penetration speed of 0.032 mm/s.

The flow rate of oil from the pump used to create linear motion for the cylinder road is plotted in Figure 13. From the plot, the maximum flow rate is 3.8×10^{-6} m^3/s. The property of the flow rate during the cylinder extension is increasing for the first half second and start to decrease up to 3 minutes during the cone penetrometer start to penetrate the soil. During penetration, again it reaches to maximum flow rate and finishes the extension of the road and starts retracting the cylinder road.

The hydraulic power graph during the soil compaction measurement model shown in Figure 14 indicates the maximum hydraulic power required to extend and retraction the hydraulic cylinder to inserts and take out the cone penetrometer is 1.9 kW. The relationship between hydraulic power and flow rate is directly proportion as shown in Figure 13 and 14.

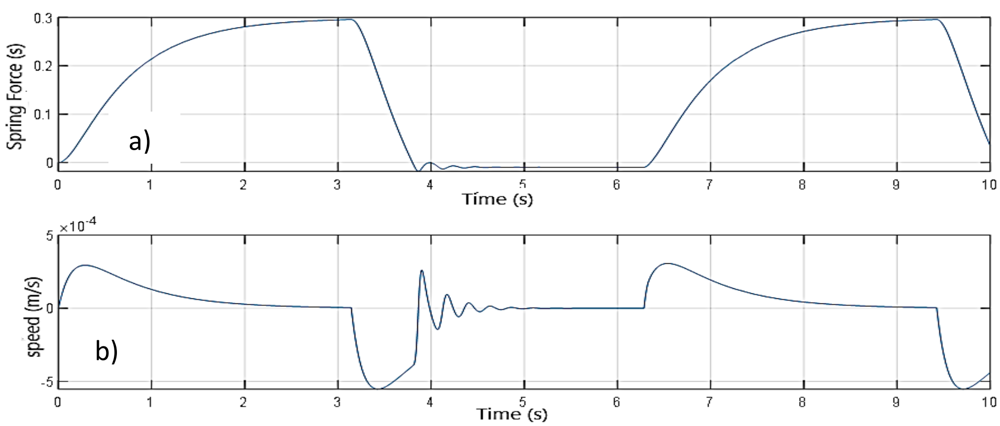

Figure 12: a) Translational spring force with respect to simulation time and b) speed require for insert the cone penetrometer in to soil with respect to simulation time

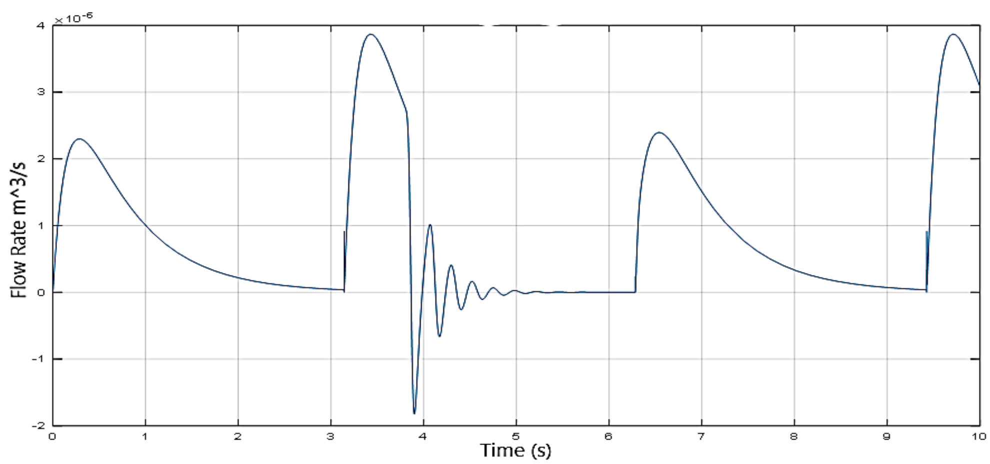

Figure 13: Pump flow rate with respect to time

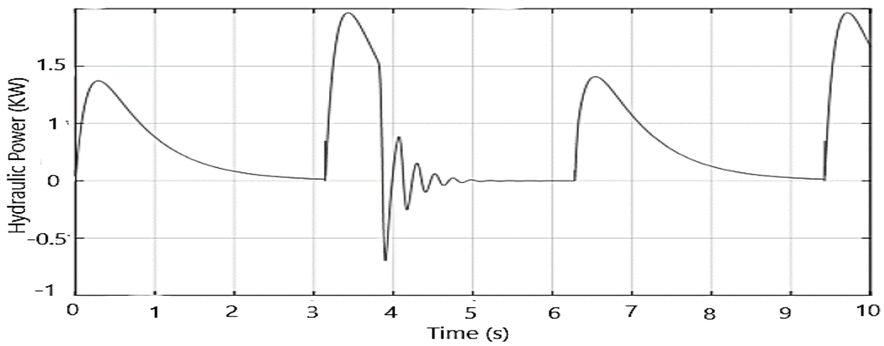

Figure 14: Pump hydraulic power with respect to simulation time

The hydraulic torque graph during the soil compaction measurement model is shown in Figure 15. It indicates the maximum torque required to extend and retract the hydraulic cylinder and to inserts and take out the cone penetrometer is 0.0502045 Nm. The minimum torque required to extend and retract the hydraulic cylinder, and to inserts and take out the cone penetrometer is 0.05020362 Nm. The relationship between hydraulic torque and flow rate is inversely proportional as shown in Figure 13 and 15.

A model of pump with constant volumetric displacement that supplies mechanical energy to a hydraulic system are susceptible for losses due to flow leakage and friction torque. The pump may operate in both the forward and reverse directions depending on the rotation of the shaft. The simulation output graph is shown in Figure 16. The result shows the pressure decreases from 38.05 Pa in a few seconds to 37.90 Pa and start increasing and reaches 38 Pa. When the cone

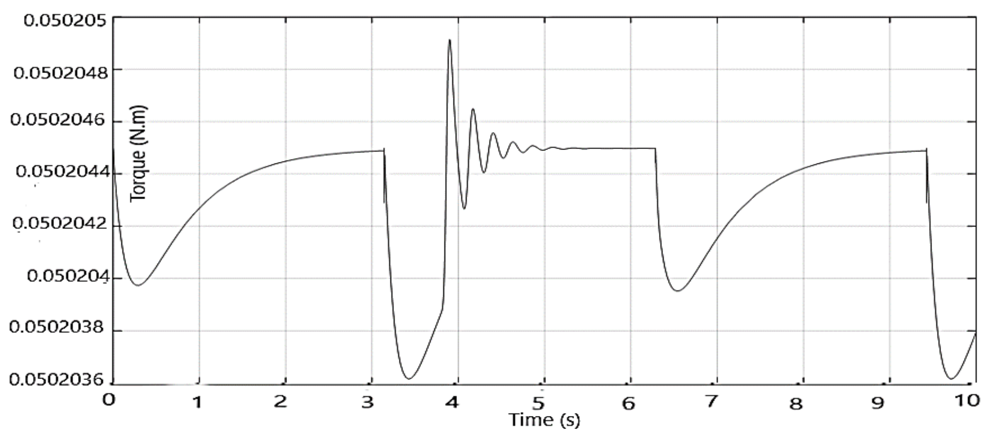

Figure 15: Pump hydraulic torque with respect to simulation time

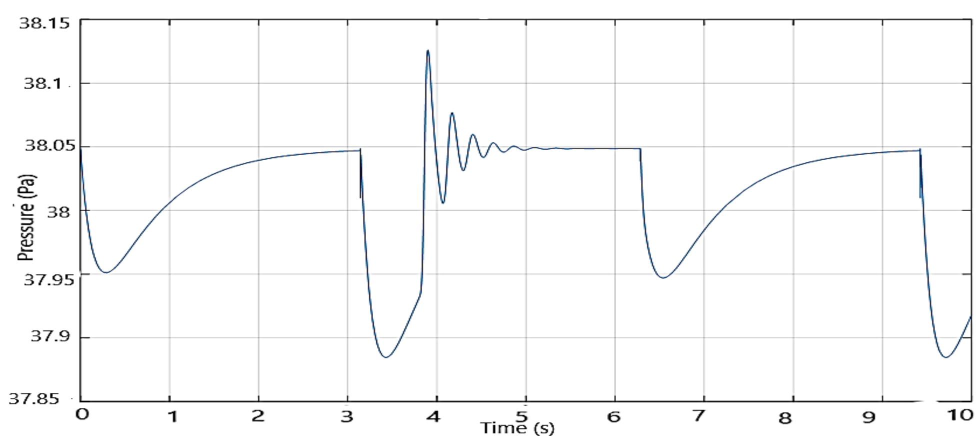

Figure 16: Pump pressure difference during extension and retraction the hydraulic cylinder with respect to simulation time.

penetrometer come into contact to the soil, the pressure decreases to minimum pressure of 37.8 Pa. During the interaction of soil and cone penetrometer, the pressure variation graph shows sine wave and finishes the first cylinder extension cycle. In the cycle, the pressure variation is from 37.87 Pa to 38.13 Pa.

4. Conclusion

In this study an attempt has been made to develop a hydraulically operated soil compaction measurement system. MATLAB Simulink 2018 is used to model and simulate parameters like vertical force as a variable mass and the soil as a stiffness and damping property. The cone index, which is the resisting pressure of soil, of 3 MPa is used for mathematical analysis. The maximum hydraulic pressure used for extend and retract the double acting cylinder for the purpose of inserting and take out the cone penetrometer is 38.05 Pa. The designed system can measure up to maximum cone index on 3 MPa but for this selected soil parameters the maximum pressure required is 38.05 Pa. From Simulink simulation the time required for the cylinder extension to insert the cone penetrometer to the soil is 3.3 seconds with the maximum speed of cylinder extension of 0.3 mm/s. The maximum downward penetration resistance force of 0.3 N and soil compaction resistance force based the model of soil as solid variable mass the maximum soil resistance force is 0.03 N. The maximum flow rate is 3.8×10^{-6} m^3/s. Flow rate is directly proportion with hydraulic power and inversely proportional with torque.

Acknowledgment

This research work is sponsored by Dire Dawa University. The authors would like to thank Adama Science and Technology University for their support in a form of facilitating PhD scholarship for the student.

Reference

Benevenute, P. A. N., Morais, E. G. d., Souza, A. A., Vasques, I. C. F., Cardoso, D. P., Sales, F. R., Severiano, E. C., Homem, B. G. C., Casagrande, D. R., & Silva, B. M. (2020). Penetration resistance: An effective indicator for monitoring soil compaction in pastures. *Ecological Indicators,* 117(2020)106647. https://doi.org/10.1016/j.ecolind.2020.106647

Chyba, J., Kroulík, M., Krištof, K., Misiewicz, P. A., & Chaney, K. (2014). Influence of soil compaction by farm machinery and livestock on water infiltration rate on grassland. *Agronomy Research*, 12(1): 59–64.

De Cicco, D., Yaghoobi, H., & Taheri, F. (2022). Development of practical semi-empirically and statistically-based equations for predicting the static and dynamic buckling capacities of 3D fibre-metal laminates. *Thin-Walled Structures*, 170: 108520.

Freitag, D. R., & Schafer, R. W. (1970). Similitude studies of soil-machine systems. *Journal of Terramechanics*, 7(2): 25-58.

Guimaraes .J, Diserens, E., De Maria, I. C., Araujo-Junior, C. F., Farhate, C. V. V., & de Souza, Z. M. (2019). Prediction of soil stresses and compaction due to agricultural machines in sugarcane cultivation systems with and without crop rotation. *Science of the Total Environment*, 681: 424-434. https://doi.org/10.1016/j.scitotenv.2019.05.009

Kumar, V., Kumar, P., Sahni, R. K., & Thomas, E. (2019). Design of tractor mounted hydraulically operated soil compaction measurement system. *Central Institute of Agricultural Engineering, Bhopal*, 8.

Mirzaliev, S., & Sharipov, K. (2020). A Review of Energy Efficient Fluid Power Systems: Fluid Power Impact on Energy, Emissions and Economics. *Acta of Turin Polytechnic University in Tashkent*, 9(4): 113-119.

Mudarisov, S., Gainullin, I., Gabitov, I., Hasanov, E., & Farhutdinov, I. (2020). Soil compaction management Reduce soil compactionusing a chain-track tractor. *Journal of Terramechanics*, 89: 1-12. https://doi.org/10.1016/j.jterra.2020.02.002

Perumpral, J. (1987). Cone penetrometer applications—A review. *American Society of Agricultural and Biological Engineers*, 30(4): 939-0944.

Phogat, V. K., Tomar, V. S., & Dahiya, R. (2015). *Soil Physical Properties*. 1st edition, Indian Society of Soil Science

Scarparea, F. V., Lier, Q. d. J. v., Camargo, L. d., R.C.M. Piresc, Ruiz-Corrêa, S. T., Bezerra, A. H. F., Gava, G. J. C., & Dias, C. T. S. (2019). Tillage effects on soil physical condition and root growth associated with sugarcane water availability. *Soil and Tillage Research*, 187: 110-118. https://doi.org/10.1016/j.still.2018.12.005

Tekin, Y., & Okursoy, R. (2007). Development of a Hydraulic-driven Soil Penetrometer for Measuring Soil Compaction in Field Conditions. *Journal of Applied Sciences*, 7(6): 918-921.

Ungureanu, N., Croitoru, Ş., Biriş, S., Voicu, G., Vlăduţ, V., Selvi, K. Ç., Boruz, S., Marin, E., & Matache, M. (2015). Agricultural soil compaction under the action of agricultural machinery. *International Symposium on Agricultural Engineering*, 43.

Wang, C., Zhang, Y., Zhang, J., & Zhu, J. (2020). Flow pattern recognition inside a rotodynamic multiphase pump via developed entropy production diagnostic model. *Journal of Petroleum Science and Engineering*, 194: 107467.

Watton, J. (2007). *Modelling, monitoring and diagnostic techniques for fluid power systems*. ISBN: 978-1-84996-591-0, Springer Science & Business Media.

Watton, J. (2009). *Fundamentals of fluid power control*. Cambridge University Press; 1st edition.