Trafficking and loading behavior on soil and sub-soil

S. K. Patel[1*], Indra Mani[2], P. K. Sundaram[3] and Jaya Sinha[1]

(1. Farm Machinery and Power Engineering, Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur)- 848125, Bihar, India;
2.Ex Head, Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi-110012, India and Vice Chancellor, Vasantrao Naik Marathawada Krishi Vidyapeeth, Parbhani-431402, Maharashtra, India ;
3.Indian Council of Agricultural Research-Research Complex for Eastern Region, Patna-800014, Bihar, India)

Abstract: The threat of soil degradation due to compaction has increased due to increasing use of heavy machinery in agriculture. An experiment was conducted in soil bin at Indian Agricultural Research Institute, New Delhi to determine the extent of compaction in the sub soil layer due to five different passes of a half chassis simulator of tractor at four normal loads of 2.71, 3.69, 4.67 and 5.65 kN. The soil of bin was alluvial with sandy loam texture. The compaction parameters e.g. bulk density and cone penetration resistance was measured at different depths i.e. upto 50 cm at intervals of 5 cm. A statistical model was developed considering soil compaction at different soil depth due to varying normal load and number of passes the bulk density in 0-15cm layer increased up to 11 passes unceasingly. The bulk density obtained in 0-15cm, 15-30cm and 30-45 cm layer were 1.52, 1.55 and 1.49 Mgm^{-3}, respectively. The increase in bulk density was more due to increased number of passes than amount of load applied in the experiment. The effect of increase in load and passes had very marginal effect on compaction at soil depth below 45 cm. The R^2 values of the developed models were 0.665, 0.864 and 0.783.

Key words: Soil compaction, Sub soil compaction, Wheel trafficking, Normal load.

Citation: Patel, S.K., I. Mani, P. K. Sundaram, and J. Sinha. 2025. Trafficking and loading behavior on soil and sub-soil. Agricultural Engineering International: CIGR Journal, 27(3): 195-207.

1 Introduction

The majority of soil compaction in modern agriculture, worldwide, is due to vehicular traffic. Increased use of power machinery system particularly heavy machines with high wheel loads has resulted into compaction of sub soil layers in agricultural fields. (Flowers and Lal, 1998). The effect of compaction is also visible in India due to increased use of agricultural machines on farms. As mechanization level is increasing with introduction of more and more tractors particularly those above 60 hp and other self-propelled agro-machines particularly combine harvester, both self-propelled and tractor drawn, the soil degradation due to compaction will increase (Van den Akker et al., 2003; Godwin et al., 2008). Presently, India's agricultural sector has witnessed significant mechanization, with tractor sales reaching a record 894,112 units in 2024and the tractor population on Indian farm is more than 6 million (Dalvi, 2025).

In recent times, the production of above 45 and 60 hp tractors is increasing due to increased use of tractors and machinery system on custom hiring and also due to use of heavy machinery like rotavator, laser leveler and balers (Singh and Mani, 2009). Tillage is major energy intensive operation which

Received date: 2023-03-25 **Accepted date:** 2025-05-05

***Corresponding author: S.K, Patel, Professor.** Farm Machinery and Power Engineering, College of Agricultural Engineering, Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur)-848125, Bihar, India, , , email-sppiari@gmail.com.

requires multiple passes of heavy machinery to prepare the seed bed traditionally. The influence of tillage practices on sub surface soil properties depends on machine parameters particularly weight of the tractors, soil parameters e.g. texture, structure and the frequency of passages of tractor machine system (Goutal et al., 2013). Sub-surface soil properties are influenced by tire parameters, soil condition, implement type, tractor weight and frequency of tractor or implement (Hamza and Anderson, 2005; Murdock et al., 1995; Taylor and Gardner, 1963).

Subsurface soil compaction is basically due to the tire's ability to transmit tractor load to the ground at soil tire interface (Jabro et al., 2012). This load gets converted into stress which enables to change sub-surface soil properties (Patel and Mani, 2011). The development of this stress is a function of tire geometry i.e. width, diameter, section height; tire type e.g. radial ply, bias ply; lug design. It is also influenced by inflation pressure, number of tires and tractor chassis design i.e. distribution of normal weight, dynamic load on the rear axle and soil physical conditions. Repeated off-the-road trafficking has been major cause of formation of compact layer below the soil surface, called hard pan which, adversely affects the root growth, development of plants and finally crop yield (Grzesiak et al., 2013; Cambi et al., 2015;Igoni and Ayotamuno, 2016; Sivarajan et al., 2018).

A number of studies have been conducted on soil compaction (Al-Adawi and Reeder, 1996; Hillel, 1998; Da Silva et al., 2003; Hamza and Anderson, 2005) and its adverse effect on root and shoot development of the plant in the compacted field (Alameda and Villar, 2009; Botta et al., 2006; Ishaq et al., 2001; Patel et al., 2020). Very few studies have been reported on sub soil compaction due to off-the road trafficking particularly in the soil conditions prevailing in India. As tractor and machine population is going to increase by 2030, there is potential threat of subsoil compaction in Indian fields on large scale keeping in view 10 million area under rice wheat cropping system.

A laboratory study on sub soil compaction was conducted to investigate the pattern of influence, of frequent movement of power machinery system with different normal loads. The central aim of the study was to determine the influence pattern of surface and sub surface soil compaction due to frequent passage of a half chassis simulator. The amount of normal load and number of passes and their effect on soil physical properties were investigated and model was developed to predict the compaction pattern with varying levels of the variable.

2 Materials and methods

The soil compaction experiments were done under controlled conditions with accurate measurement of the study variables and the parameters of soil compaction at different depth in an indoor soil bin, in the Division of Agricultural Engineering at Indian Agricultural Research Institute, New Delhi.

2.1 Experimental setup

To conduct the compaction test in the soil bin a traction device with provision to vary normal load, centre of gravity and other pertinent parameters was used (Mani, 1995). This traction device was basically a half chassis simulator of a tractor with front and rear wheel and necessary accessories (Figure 1). The heart of the tractive system was a structural unit called half chassis simulator of a tractor. It resembled a vertically cut half section of a tractor. It has provision to mount rear and front wheels, a platform for ballasting rear wheel and distribution of weight, necessary instrumentation and safe power supply system besides operator's seat.

The main units of this simulator were rear traction wheel, front towed wheel, power transmission train, and guide plates. The rear traction wheel of a 2-wheel drive tractor was of paramount importance in the study as it developed traction at soil-tire-interface. A commercially available tractor wheel with size 8-18 and 4 ply rating having a load bearing capacity of 6.00 kN was used as rear traction wheel. This wheel was mounted on a shaft, width 4.0 cm diameter and

63 cm length. Front wheel assembly was mounted on the half-chassis simulator with the help of two guide arms made with angle iron of 50 mm × 50 mm × 6 mm size. This assembly could be positioned anywhere across the width of simulator on the shaft with the help of two bushes of 8.5 cm length, each connected to guide arms. The chassis of the simulator was designed in such a manner that it could accommodate all essential units of the system including power transmission train. In this experiment constant wheel base of 1.345 m was kept during the complete experiment process.

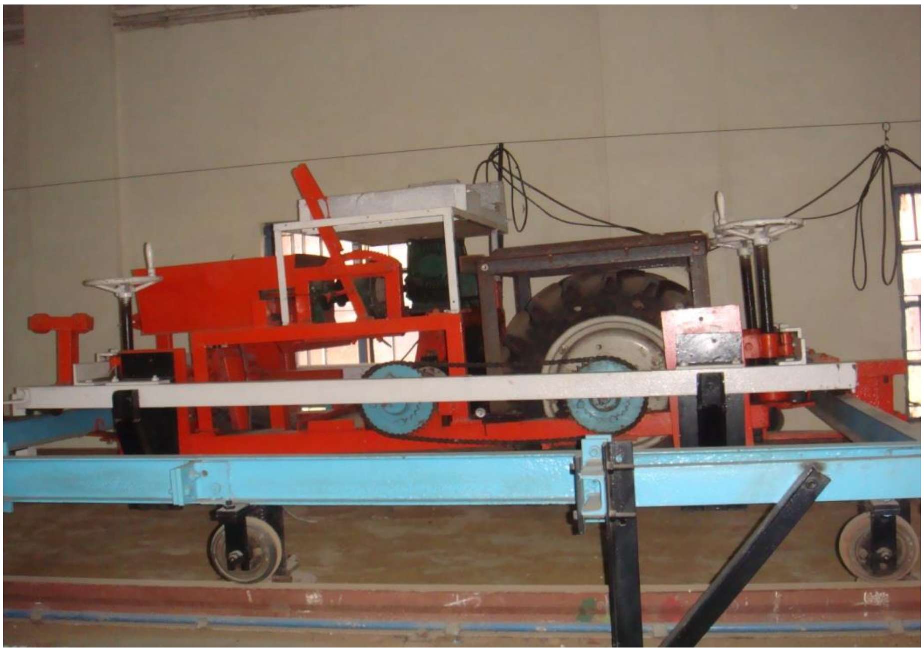


Figure 1 Experimental setup

A seat for operator was provided which rested upon the main base frame. The reaction due to operator weight was neutralized in a position such that the operator could have easy access to clutch handle. A foot rest, made of angle iron was also provided on the main base frame. The half chassis simulator of tractor was kept in an enclosure of a structural frame with angle iron of 75 mm × 75 mm × 10 mm dimension. Overall length and width of this frame were kept as 262 cm and 175 cm. This structural frame was mounted on the main frame with the help of roller wheels. The simulator was suspended in a free float condition, free from all sides except at the rear. At the rear end of the simulator, it was connected to the main base frame through rigid vertical arm. This connection was done with the help of frictionless ball and socket joints using ball bearing, thus making a free hinge at the joint.

Since it was single wheel machine, a frictionless continuous support was required in both sides of the simulator’s length to achieve this position. Four guide plates, one each at four corners of the simulator were fastened with the help of nut and bolts. These plates were supported by another set of plates fitted with universal roller at the interface of two guide plates. These rollers, movable in any direction, were positioned at predetermined locations on the plate to meet the system’s requirement. The top roller was at 10 cm distance from the upper end making a triangle with other two base rollers located each at 10 cm distance from the upper end making a triangle with other two base rollers located each at 10 cm distance from two sides; the triangle height was equivalent to 37 cm. Overall dimensions of the outer and inner plates were 51 cm × 19 cm × 1.5 cm and 56 cm × 23 cm × 1.5 cm, respectively. This kind of suspension with the help of frictionless universal roller guide plates and free hinge at the joint of simulator and load cell could provide freedom for wheel shrinkage in accordance with normal load, pull and slip. This could also help in transmitting thrust through traction wheel. The guide plates helped to keep the traction unit in balanced vertical posture and allowing it to function as an independent half chassis tractor in operation.

The simulated half chassis tractor experienced soil reaction at rear and front wheels as good as in the field. The test run could be conducted only in forward direction so it became necessary to lift the traction unit to put it on a fresh track. The traction unit could be lifted off the soil surface by a mechanical rotating screw lift arrangement. These screws were made from 40 mm diameter steel rod of a length of 46 cm. At the top of the screw, lift arrangement, wheel handle with 26 cm diameter was provided, one each for four screws, to make the lifting and lowering of the traction unit easy. The base of the ball and socket joints were welded at the four corners of the simulator. There was also arrangement to fix the simulator at different vertical positions with the help of split bush mechanism tightened with nut and bolt. This facilitated the backward movement of the simulator without disturbing the prepared track. The 5 TPI screws were attached to the body frame of the simulator through ball and socket joints enabling the screw to rotate at different cone angles. The application of different normal loads was required in the experiment so a load application platform was provided to apply load upto 6.00 kN, on the traction wheel**.**

In this setup two automatic cut-off limit switch were provided giving provision to have an idle length of 6.0 m on either side of the bin for engaging and disengaging the simulator to drive motor mounted on it. Thus, a usable track length of 13 m was obtained. The effective soil bin length of 13.0 m was divided into four sub- lengths of 3.25 metre. The total depth of soil in the bin was 70cm only.

2.2 Plan of experiment

The study was planned to determine the effect of different levels of normal load and number of passes on soil compaction parameters. The observations on compaction parameters like bulk density and penetration resistance were taken by at 4 different loads of2.71 (L_1), 3.69 (L_2), 4.67 (L_3) and 5.65 (L_4) kN and 5 different passes i.e. 1 (P_1), 3 (P_2), 5 (P_3), 7 (P_4) and 11 (P_5) number at 10 different depth levels i.e. 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45 and 45-50 cm. Using the data obtained from the experiment on the soil bin a model was developed to predict the bulk density and cone penetration resistance with varying levels of normal load and number of passes at different soil depths. A factorial design analysis was followed in planning the experiment keeping the factors of the variables normal load and number of passes. The SPSS was used to analyze the data to determine the influence pattern of bulk density and penetration resistance.

2.3 Experimental procedure

The test setup had provision to mount different loads on rear tire and could be run on same track for multiple passages. Four levels of additional load of 0.98, 1.96, 2.94 and 3.92 kN were mounted on the rear tire to give total four levels of normal load on tire-soil interface. The dead load on rear tire without any additional load was determined as 1.73kN.To determine sub-soil compaction soil samples for bulk density measurement were collected upto a total depth of 70 m at an interval of 5 cm. Thus, at one location a total of 14 samples were collected. For all soil depths, moisture content was also measured. A dynamic cone penetrometer was used for measuring penetration resistance. It consisted of nylon rope of 2.5 m attached to a weight of 0.5 kg mounted over the pulley which facilitated smooth lift of the weight. The movement of weight was guided in a cylinder. The cylinder of the penetrometer, housing was placed in the sleeve of the tripod stand to permit unidirectional motion. The diameter and height of the cylinder is 10 cm and 75 cm, respectively. The effective height of the cylinder was 0.50 m. The cylinder was attached with cone rod which is 21 mm diameter and had tipe angle of cone as 30 degree. After placing the penetrometer at the predetermined location, it was set vertically by positioning the tripod legs. After ensuring freefall of the weight, 10 numbers of strokes were given so as to flush the cone base with the soil surface. The number of strokes was recorded for a cumulative penetration up to 50 cm of depth. The penetrometer measurements can either be expressed as the number of strokes per meter of penetration or as the average soil resistance for each depth of soil travelled by each stroke of the hammer. This approach generates an average resistance (Joulecm^{-1}) across the depth the cone travels.

To begin with, a normal load (L_1) of 2.71 kN was applied and the test setup was run just for one pass (P_1), at a forward speed of 1.2 kilometer per hour. The soil physical parameters e.g. bulk density, penetration resistance and moisture content were measured for different soil depths. To ascertain the impact of frequency of passes on compaction of sub soil layer, the test tractor was run for 3 number of passes at L_1 load of 2.71 kN with three replications, and after each set of passes the soil physical parameters were measured for different soil depths. Similarly, with first load (L_1) the test run for 5, 7 and 11 passage were done and observations were taken. In the same manner other experiments were conducted for remaining normal loads i.e. L_2, L_3& $L_4$with respective number of passes and required data were collected.

Figure 2 Normal load on the experimental setup

The data was analyzed to determine the influence of the study variables i.e. normal loads and number of passes on compaction parameters i.e. bulk density and penetration resistance.

2.4 Statistical model

2.4.1 Bulk density and penetration resistance prediction model

Empirical relationships were obtained by expressing soil bulk density and penetration resistance at different soil depth layers as a function of normal load on tractive system and its passes. The following equations were developed using step wise multiple regression on different values of the variables.

$$ln\ BD = K_1 + K_2\ L + K_3\ P + K_4\ D \quad (1)$$

$$ln\ PE = A_1 + A_2\ L + A_3\ P + A_4\ D \quad (2)$$

Where: BD = bulk density, Mgm^{-3}

PE = penetration resistance, Jcm^{-1}

L = amount of load, kN

P = number of pass

D = depth layer, cm (5-70)

K_1, $K2$,. , $K_4$and A_1, A_2,….A_4 are constants.

2.4.2 Penetration resistance with known to bulk density

The different values of the variables considered were used to identify an empirical relationship expressing soil bulk density as a function of penetration resistance and soil depth layers. Determination of the following equations of the model to which the observed values adjusted was accomplished using the step-wise multiple regression technique.

$$ln\ PE = B_1 - B_2 ln\ D + B_3\ ln\ BD \quad (3)$$

Where:

BD = bulk density, Mgm^{-3};

PE = penetration resistance, Jcm^{-1};

D = depth layer, cm (5-70);

B_1, B_2 and B_3 = constants.

2.4.3 Sensitivity analysis of the model

A sensitivity analysis was carried out for the parameters influencing the bulk density and penetration resistance at different soil depths v.z. number of pass and normal load. While performing the sensitivity analysis, all the parameters were varied in a definite ratio e.g.by increasing or decreasing the parameters randomly by 5% to its estimated values.

3 Results and discussion

The initial bulk density of soil ranged between 1.33 to 1.40 Mgm^{-3}. The highest bulk density of 1.43 Mgm^{-3} was observed between10 to 20 cm depth level, while the lowest bulk density of1.33 $Mgm^{-3}$was observed between 45 to 50 cm soil depth. A variation of 9.2% to 12.5% in moisture content was observed upto 50cm depth during the experimentation in soil bin.

3.1 Effect of normal load and passes on bulk density of sub-soil layer

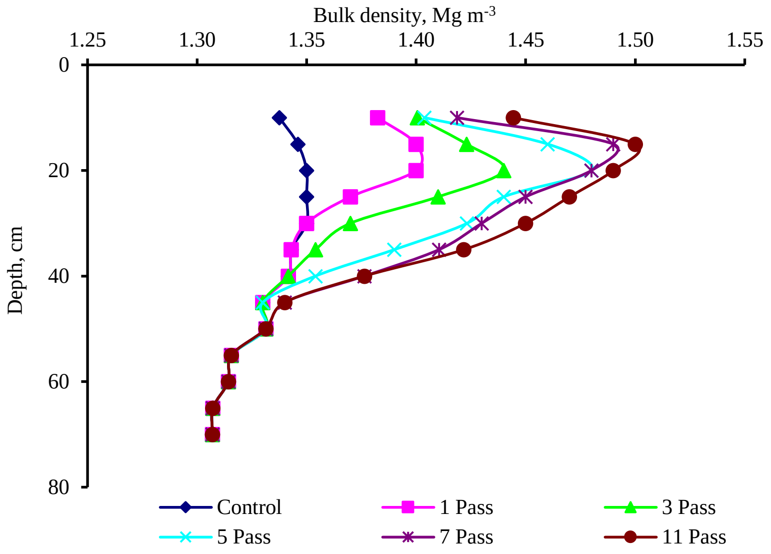
To investigate the soil compaction effect at different depths, the compaction parameters are investigated at soil depth of 0-15, 15-30, 30-45 and above 45 cm which represents surface, sub-surface and below sub-surface soil layers. In general, the bulk density in 0-15 cm depth layer increased with increase in loads and number of passes. The maximum load of 5.65 kN and largest number of passes of 11 caused maximum soil bulk density of 1.48, 1.52 and 1.56 Mgm^{-3} for different depth levels of 0-5, 5-10 and 10-15 cm, respectively, in the same order. At a normal load of 5.65 kN, the increase in bulk density due 1 to5number of passes was observed as2.76% whereas for 7 to 11 number of passes the same was 0.7%, only. The bulk density was influence by normal load as well as number of passes.

For different normal loads, the compaction increased more for initial passes because initially soil was loose. However, bulk density in this depth zone increased significantly up to 11 passes. At 15 cm i.e. sub-soil layer, compaction was caused by transmittance of stresses developed at soil tire interface. Once the soil is compacted, the stresses could be transmitted effectively.

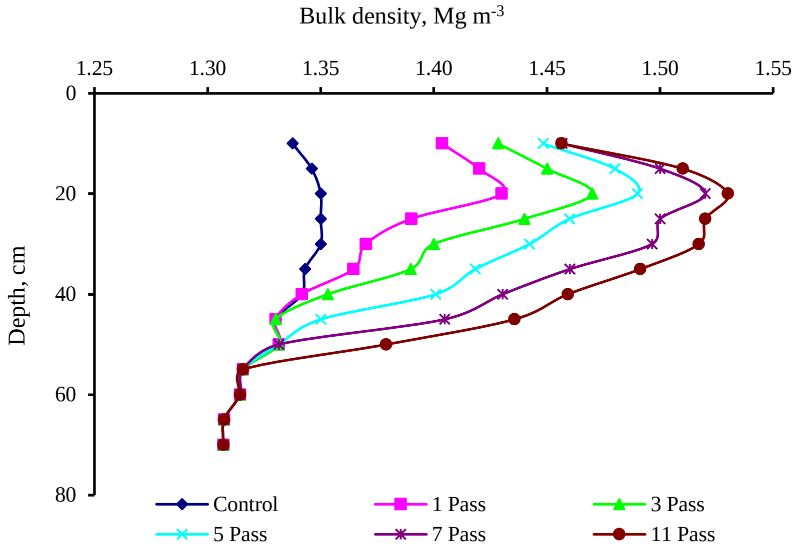
In general, the bulk density in 15-30 cm depth layer increased with increase in loads and number of passes, however there was only marginal variation in the density of 15-30 cm layer with respect to that of 0-15 cm layer, Figures 3 (a to d). However, with increase in normal load and no of passes the bulk density in this layer increased in whole depth range. Higher load and higher number of passes facilitated more effective sub surface soil compaction as stresses could be transmitted effectively in soil with high density.

The highest amount of normal load of 5.65 kN and maximum of 11 passes, the sub soil layer of 15-30 cm experienced maximum compaction (bulk density 1.55 Mgm^{-3}); and with lowest load and maximum number of passes also the 15-30 cm layer experience highest bulk density (1.45 to 1.52 Mgm^{-3}) whereas for same load and pass 0-15 cm experienced little bit less compaction and 30-45 cm soil layer experienced further less bulk density of 1.38 Mgm^{-3}.

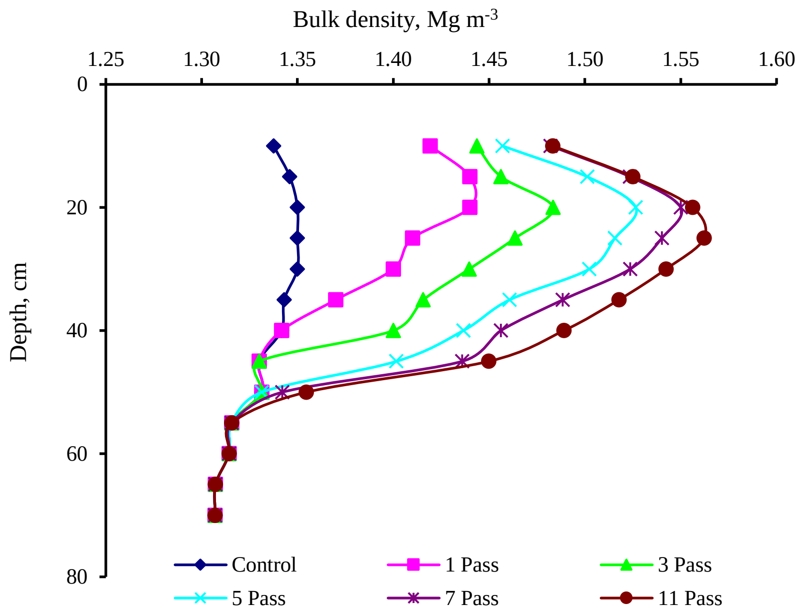
In 30-45 cm depth layer also, the bulk density registered increase with increase in loads and number of passes. The maximum load of 5.65 kN and largest number of passes of 11 caused maximum soil bulk density of 1.53, 1.48 and 1.46 Mgm^{-3} for different depth levels of 30-35, 35-40 and 40-45 cm, respectively, in the same order. Thus, this layer experienced relatively less compaction in comparison to 0-15 and 15-30 cm layers in terms of bulk density. Like previous layers at given load, bulk density increased with increase in number of passes for example at a load of 4.67 kN the bulk density for 1, 3, 5, 7 and 11number of passes were observed as 1.35, 1.38, 1.43, 1.46 and 1.49 Mgm^{-3}, respectively. The increase in bulk density in this layer also was more pronounced for initial 5 passes, but for more than5 passes the influence reduced.



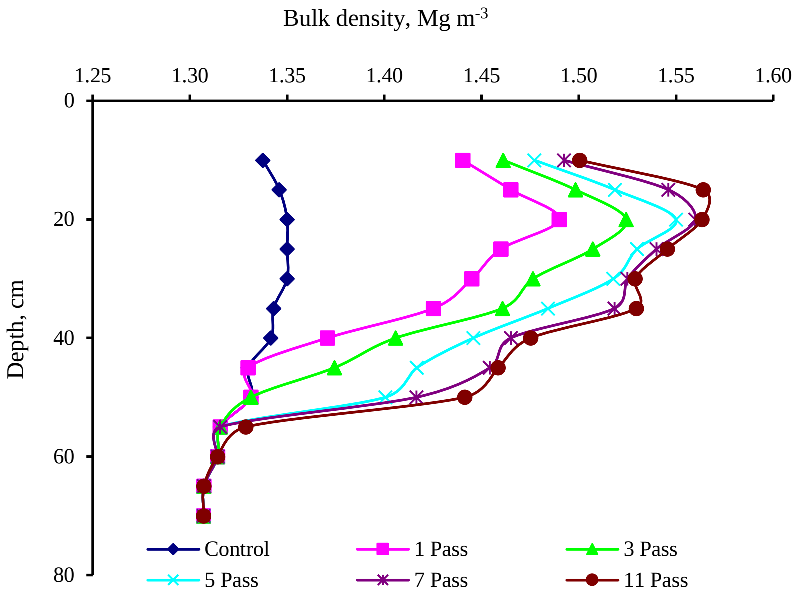
(a) At normal load of 2.71 kN



(b) At normal load of 3.69 kN



(c) At normal load of 4.67 kN



(d) At normal load of 5.65 kN

Figure 3 Variation in bulk density with depth at varying no of passes

In the compacted soil the rate of compaction will be relatively less which was visible from the observation which is why the incremental effect on bulk density decreased with increase in number of passes due to sufficient initial compaction. However, in this depth zone also compaction continued with more number of passes and more loads up to 11 passes. This is because in this sub-soil layer also compaction was caused by transmittance of stresses developed at surface.

At lower depth of 30 to 45 cm the impact of higher load and higher passes was more visible; the normal load of 4.67 and 5.65 kN caused same compaction (1.49 Mgm^{-3}) after 11 passes. The lower loads of 2.71 kN could cause maximum density of 1.38 both at 7 and 11 passes in this soil layer however, with increase in load a synergic effect between load and passes were observed; the maximum compaction with bulk density 1.46 Mgm^{-3} was observed for 3.69 and 11 passes and 4.67 kN and 7 passes.

At soil depth of 45-60 cm the normal loads of 2.71, 3.69 and 4.67 kN caused same bulk density of about 1.32 Mgm^{-3} for all the passes from 1 to 11. The initial bulk density in this sub-soil layer was 1.32 Mgm^{-3}. Thus, the normal load up to 4.67 kN and increase of passes 1 to 11 did not cause any difference on bulk density on this layer. Only the highest load of 5.65 kN at more than 7 passes caused compaction with a bulk density 1.35 to 1.36 Mgm^{-3}. Thus, the effect of increasing load and passes almost ceases beyond 45 cm except in the case of higher loads and higher passes that too marginally. This also confirms from the statistical analysis, Table 1.

3.2 Effect of normal load and passes on penetration resistance

Soil resistance is the most important parameters for evaluation of soil compaction. Soil resistance value determined the strength of soil. Soil compaction is the major cause for reduced root penetration of field crops; often to the point that water and nutrient uptake, and, hence, plant growth and yield get affected adversely. The phenomenon is more pronounce when soil strength reached critical levels due to natural or induced compaction. The initial penetration resistance was observed as 10.77, 8.63, 7.18 and 6.97 Jcm^{-1} at 0-15, 15-30, 30-45 and 45-50 cm soil depth, respectively.

In general, the penetration resistance in 0-15 cm depth layer increased with increase in loads and number of passes. The maximum load of 5.65 kN and largest number of passes of 11 caused maximum penetration resistance for different depth levels. At given load, penetration resistance increased with increase in number of passes. At a load of 3.69 kN the penetration resistance of 15.22, 17.99, 20.58, 21.38 and 23.17 Jcm^{-1} were observed for 1, 3, 5, 7 and 11 number of passes, respectively. As in case of bulk density, penetration resistance also increased continuously with increase in passes, however, the rate of compaction reduced after 7 passes. At a normal load of 5.65 kN, the increase in penetration resistance for increase in passes from 1-7 was 21.50to 33.73 Mgm^{-3} i.e. 56.9% whereas for 7 to 11 passes the same was33.73 to 35.84 Jcm^{-1} i.e. 6.3%.

Table 1 F- value for bulk density

Source	d. f.	Soil depth, cm			
		0-15	15-30	30-45	45-70
load	2	64.845**	234.403**	276.646**	44.801**
pass	3	51.786**	248.932**	333.656**	80.222**
load * pass	6	0.065	5.455**	14.438**	1.577
R^2		0.957	0.973	0.980	0.962

Note: ** significant at 1%, *significant at 5%, others non-significant

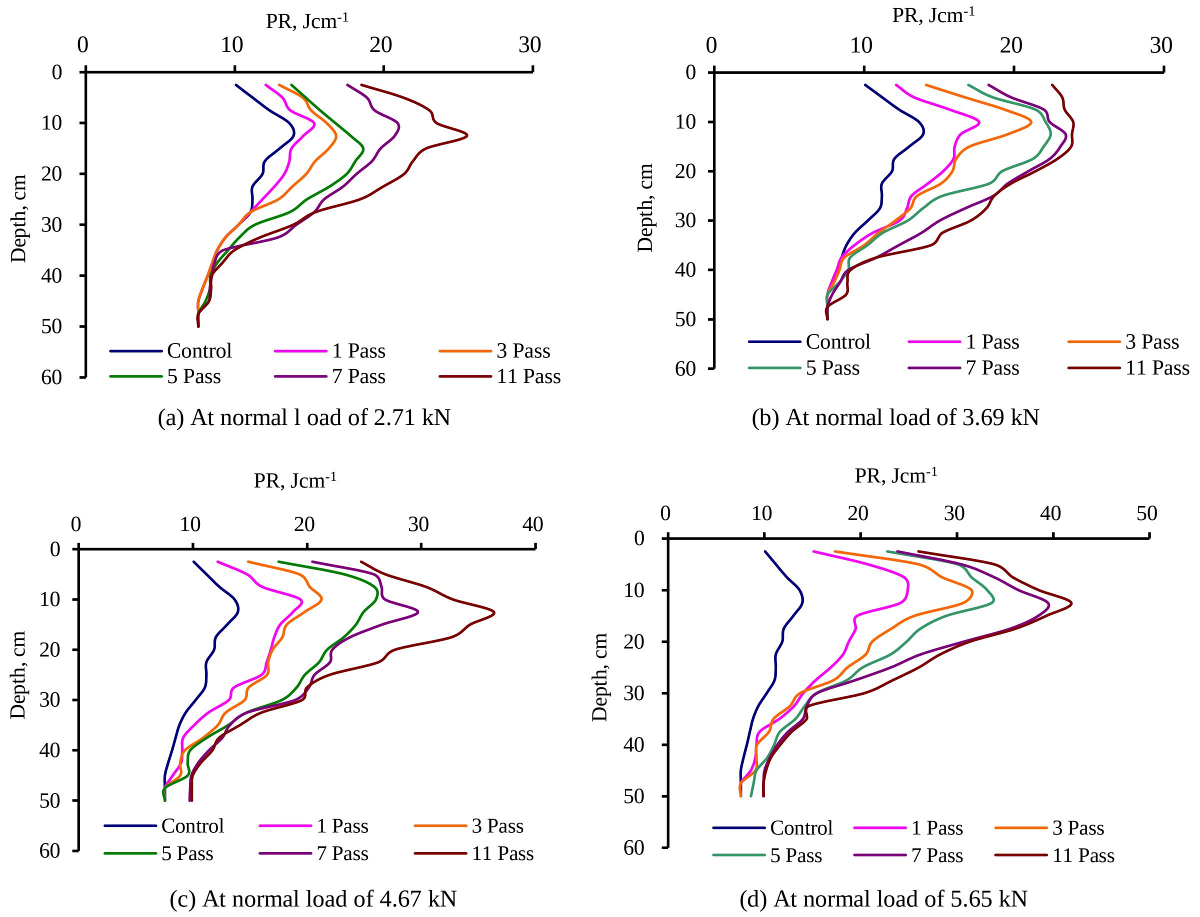


Figure 4 Variation in penetration resistance with depth at varying no of passes

In the 15-30 cm layer, the observed penetration resistance was relatively less in comparison to top layer of 0-15cm.The soil compaction process in the bin was not as in the open field so the lower layers could not develop strength as much as the upper layer. However, the penetration resistance of 15-30cm layer increased with increase in loads and number of passes. The maximum load of 5.65 kN and largest number of passes of 11 caused maximum penetration resistance. Penetration resistance of were observed 34.70, 28.14 and 19.85 Jcm^{-1} for maximum number of passes and load at depth levels of 30-35, 35-40 and 40-45 cm, respectively, in the same order. At given load, penetration resistance increased with increase in number of passes. The increase in penetration resistance in this layer was more pronounced for initially 5 passes, the influence decreased after 5 passes. At a normal load of 5.65 kN, the increase in penetration resistance for 5 number of passes was 24.9% whereas for 7 to 11 passes the same ranged between 9.9%, Figures 4 (a to d). The penetration resistance increased with increase in number of passes in this depth zone also. In this case also the higher normal load and higher passes had pronounced effect on sub surface soil compaction.

The low load 2.71 kN with highest number of passes caused almost same bulk density (1.46 Mgm^{-3}) at 0-15 and 15-30 cm layer whereas the highest loads (4.67-5.65 kN) and higher number of passes (7-11) bulk density ranging between 1.50 to 1.52 whereas the same load and passes caused bulk density of ranging 1.54 to 1.55 in 15-30 cm layer. This confirms the synergic effect of load and passes on compaction.

In 30-45 cm depth layer also, the penetration resistance registered increase with increase number of passes particularly at higher loads. The maximum load of 5.65 kN and largest number of passes of 11 caused maximum penetration resistance of 14.50, 12.24 and 10.35 Jcm^{-1} for different depth levels of 30-35, 35-40 and 40-45 cm, respectively, in the same order. Thus, the penetration resistance in this layer was relatively less in comparison to 0-15 and 15-30 cm layers. Also, at given load, penetration resistance increased with increase in number of passes; at a load of 4.67 kN the observed penetration resistance for 1, 5 and 11 passes were observed as 9.48, 11.31 and 12.13 Jcm^{-1} respectively. The loads had increasing influence on increase of penetration resistance as in this layer at loads of 2.71, 3.69, 4.67 and 4.65 kN, the increase in penetration resistance for increase in number of passes from 1 to 5 were 0.53, 0.56, 1.83 and 2.09 Jcm^{-1} which was in increasing order. However, the increase in penetration resistance caused by increase in number of passes due to 7 to 11 passes was relatively less.

However, in this depth zone also compaction continued up to 11 number of passes at higher loads. Sub-soil compaction was observed as a dynamic process as in this layer also; the penetration resistance at lowest normal load of 2.71 kN and 11 passes was observed as 9.32 Jcm^{-1} whereas the same at highest load of 5.65 kN and for 1 and 3 passes was 9.50 and 10.26 Jcm^{-1}, respectively. For the first two load there was no appreciable variation in penetration resistance up to 1 to 7 passes; at highest load of 5.65 kN and for largest number of passes of 11, the highest penetration resistance was observed; as such the variation in penetration resistance in this zone was not very significant. This indicates that increase in soil strength, in this layer, due to load and passes was marginal only.

At soil depth of below 45 cm the normal loads of 2.71, 3.69 and 4.67 kN caused almost same penetration resistance of about 7.55 Jcm^{-1} for all the passes from 1 to 11. The initial penetration resistance in this sub soil layer was 7.55 Jcm^{-1}. Thus, the normal load up to 4.67 kN and increase of passes 1 to 11 did not cause any difference on penetration resistance on this layer. Only the highest load of 5.65 kN at more than 7 passes caused compaction with a penetration resistance 8.74 to 9.91 Jcm^{-1}. Thus, the effect of increasing load and passes almost ceases beyond 45 cm except in the case of higher loads and higher passes that too marginally. This also confirms from the statistical analysis.

3.3 Analysis of variance for bulk density

The normal load on tractive system and number of passes influenced bulk density in soil depth range of 0-15, 15-30 and 30-45 cm at 1% level of significance, however, beyond 45 cm soil depth, the influence was not significant, Table 1. Also, these variables interacted significantly to influence bulk density in the depth range of 15-30 and 30-45 cm at 1% level of confidence interval, respectively. In pair wise comparison, at 30-45 cm soil depth, it was observed that pair L_1 and L_3 and L_3 and L_4 was significantly different with respect to their influence on bulk density. Similarly, at 0-45 cm the pass pair was significantly different with respect to their influence on bulk density.

3.4 Analysis of variance for penetration resistance

The normal load on tractive system and number of passes influenced penetration resistance in soil depth range of 0-15, 15-30 and 30-45 cm at 1% level of significance, however, beyond 45 cm soil depth, the influence was not significant, Table 2. Also, these variables interacted significantly to influence penetration resistance in the depth range of 0-45 cm at 1% level of confidence interval, respectively, Table 2.

Table 2 F- value for penetration resistance

Source	d. f.	Soil depth, cm			
		0-15	15-30	30-45	45-70
load	2	279.57**	621.67**	361.13**	36.454**
pass	3	159.60**	566.84**	162.38**	23.514**
load * pass	6	5.510**	12.191**	7.481**	.736

Note: ** significant at 1%, *significant at 5%, others non-significant

3.5 Development of regression model

Different values of the variables included in the model of Equations1 and 2 were taken from lab experiment (Tables 3 and 4). For validation of this model, the measured bulk densities in the field condition could be used. On applying the model of Equations4 and 5 to the data, the following equation was obtained:

$$ln\ BD = 0.305 - 0.002D + 0.006\ P + 0.016L \quad (4)$$

$$ln\ PE = 2.848 - 0.028D + 0.031\ P + 0.080L \quad (5)$$

Table 3 Parameters of Equation 1

	Equation parameter			
	K1	K2	K3	K4
Value	0.305	-0.002	0.006	0.0016
Standard error	0.006	0.000	0.000	0.001
Significance level	***a	***	***	***
Partial correlation		-0.676	0.628	0.576
Regression	R2= 0.665			

Note: [a] Significance level: ***, P <0.001

Table 4 Parameters of Equation 2

	Equation parameter			
	A_1	A_2	A_3	A_4
Value	2.848	-0.028	0.031	0.080
Standard error	0.031	0.000	0.002	0.006
Significance level	***[a]	***	***	***
Partial correlation		-0.922	0.540	0.473
Regression	R^2 = 0.864			

Note: [a] Significance level: ***, P <0.001

3.6 Bulk density and penetration prediction model

Different values of the variables included in the model of Equation 3 were taken under lab conditions (Table 5). On applying the model of Equation6 to the data, the following equation was obtained:

$$ln\ PE = 2.359 - 0.402\ ln\ D + 4.164\ ln\ BD \quad (6)$$

Table 5 Parameters of Equation 3

	Equation parameter		
	B_1	B_2	B_3
Value	2.359	-0.402	4.164
Standard error	0.107	0.014	0.222
Significance level	***[a]	***	***
Partial correlation		-0.762	0.609
Regression	R^2= 0.783		

Note: [a] Significance level: ***, P<0.001

3.7 Sensitivity analysis

A sensitivity analysis was carried out for the parameters influencing the bulk density and penetration resistance at different soil depths *viz.* number of pass and normal load. While performing the sensitivity analysis, all the parameters were varied in a definite ratio e.g.by increasing or decreasing the parameters randomly by 5% to its estimated values.

3.7.1 Bulk density

The variation in bulk density was 6.19 to -6.50 per cent, at 5% increase in soil depth layer keeping constant number of pass and normal load whereas the same was 0.93% to -19.52% at 5% decrease of soil depth with same load and pass Table 6.

Table 6 Sensitivity of bulk density to translation

	Normal load	Number of pass	Soil depth	Combined
5% increase				
Max. variation (4.07 kN, 5, 20 cm)	5.50	5.86	6.19	5.46
Min. variation (4.73 kN, 11, 10 cm)	-7.30	-7.03	-6.50	-6.67
5% decrease				
Max. variation (4.73 kN, 5, 15 cm)	1.48	1.00	0.93	1.78
Min. variation (4.73kN, 1, 50 cm)	-19.18	-19.93	-19.52	-18.68

3.7.2 Penetration resistance

The 5% increase in normal load the variation in penetration resistance was 32.39 to -75.53 per cent whereas the same was 37.29 to -64.53 per cent for decrease of 5% in normal load with same pass and depth, Table 7. It was observed that for the same per cent variation in the parameters i.e. normal load, number of pass and soil depth, the per cent variation in penetration resistance is sensitive to increasing as well as decreasing the parameters.

Table 7 Sensitivity of penetration resistance to translation of normal load, number of pass and soil depth

Variable	Normal load	Number of pass	Soil depth	Combined
5% increase				
Max. variation (4.73 kN, 7, 10 cm)	32.39	34.08	35.70	32.41
Min. variation (4.07 kN, 1, 5 cm)	-75.53	-70.24	-68.88	-74.74
5% decrease				
Max. variation (4.73 kN, 7, 10 cm)	37.29	35.68	34.07	37.28
Min. variation (4.07 kN, 1, 5 cm)	-64.53	-69.64	-71.00	-65.27

3.7.3 Prediction of bulk density vs penetration resistance

An increase of 5%in bulk density and soil depth layer the variation in penetration resistance was 5.70 to -8.56 per cent, however the same was 6.93 to -7.18 per cent with decrease of 5% in input parameters, Table8. It is observed that for the same per cent variation in the parameters i.e. bulk density and soil depth layer the variation in penetration resistance was almost same. Hence, this equation can be used to determine the bulk density of soil at different depth of soil.

Table 8 Sensitivity of bulk density to translation of PR and soil depth

Variable	Penetration resistance	Soil depth	Combined i.e. both decreased
5% increase			
Max. variation (4.07 kN, 1, 5 cm)	5.35	5.70	5.07
Min. variation (2.73 kN, 5, 10 cm)	-8.24	-7.84	-8.56
5% decrease			
Max. variation (4.07 kN, 1, 5 cm)	6.64	6.27	6.93
Min. variation (2.73kN, 5, 10 cm)	-6.77	-7.18	-6.43

4 Conclusions

The average increase in bulk density and penetration resistance was more due to increased number of passes than due to increase in normal load at relatively higher load condition, in the given range of load and passes. The effect of increase in load and passes had very marginal effect on compaction at soil depth below 45 centimeters.

References

Al-Adawi, S. S., and R. C. Reeder.1996. Compaction and sub-soiling effects on corn and soybean yields and soil physical properties. *Transactions ofthe ASAE*, 39(5): 1641-1649.

Alameda, D., and R. Villar. 2009. Moderate soil compaction: implications on growth and architecture in seedlings of 17 woody plant species. *Soil &Tillage Research*, 103(2):325-331.

Botta, G. F., D. Jorajuria, H. Rosatto, and C. Ferrero. 2006. Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. *Soil &Tillage Research*, 86(1):9-14.

Cambi, M., G. Certini, F. Neri, and E. Marchi.2015. The impact of heavy traffic on forest soils: a review. *Forest Ecology and Management*, 338: 124-138.

Dalvi, A. 2025. Record-breaking year for tractor sales at 894,112 units. Availableat:https://www.autocarpro.in/analysis-sales/record-breaking-year-for-tractor-sales-at-894112-units-mahindra-share-rises-to-42-124297. Accessed 01. 05.2025.

Da Silva, A. P., S.Imhoff, and M. Corsi.2003. Evaluation of soil compaction in an irrigated short-duration grazing system. *Soil &Tillage Research*, 70(1):83-90.

Flowers, M.D., and R. Lal. 1998. Axle load and tillage effects on soil physical properties and soybean grain yield on a mollicochraqualf in northwest Ohio. *Soil &Tillage Research*, 48(1-2): 21-35.

Godwin, R., G. Spoor, B. Finney, M. Hann, and B. Davies. 2008. The current status of soil and water management in England. Stoneleigh, Warwick: Royal Agricultural Society of England.

Goutal, N., T. Keller, P. Défossez, and J. Ranger. 2013. Soil compaction due to heavy forest traffic: measurements and simulations using an analytical soil compaction model. *Annals of Forest Science*, 70(5):545-556.

Grzesiak, S., M. T. Grzesiak, T. Hura, I. Marcińska, and A. Rzepka. 2013. Changes in root system structure, leaf water potential and gas exchange of maize and triticale seedlings affected by soil compaction. *Environmental and Experimental Botany*, 88: 2-10.

Hamza, M.A., and W.K. Anderson.2005. Soil compaction in cropping systems a review of the nature, causes and possible solutions. *Soil &Tillage Research*, 82(2):121-145.

Hillel, D. 1998. *Environmental Soil Physics*. San Diego, CA, USA: Academic Press.

Igoni, A. H., and J. M. Ayotamuno. 2016. Maize yield response to induced compaction in a sandy-loam soil. *Sustainable Agriculture Research*, 5(2): 57-64.

Ishaq, M., A. Hassan, M. Saeed, M. Ibrahim, and R. Lal. 2001. Subsoil compaction effects on crops in Punjab. Pakistan I. Soil physical properties and crop yield. *Soil and Tillage Research*, 59(1-2):57-65.

Jabro, J., R. Evans, and W. Iversen. 2012. Freeze-thaw cycles effects on soil compaction in a clay loam. *Geophysical Research Abstracts*, 14: EGU2012-1688.

Mani, I. 1995. Determination of design parameters of small tractor. Ph.D. diss., IARI, New Delhi.

Murdock, L., T. Gray, F. Higgins, and K. Wells. 1995. Soil Compaction in Kentucky. Lexington, Kentucky: Publication of the Cooperative Extension Service. University of Kentucky, College of Agriculture.

Patel, S.K., and I. Mani. 2011. Effect of multiple passes of tractor with varying normal load on subsoil compaction. *Journal of Terramechanics*, 48(4): 277–284.

Patel, S.K., I. Mani, and P. K. Sundaram. 2020. Effect of subsoil compaction on rooting behavior and yields of wheat. *Journal of Terramechanics*, 92: 43-50.

Singh, G., and I. Mani. 2009. Agricultural mechanization in India: Status and future challenges. Bankok, Thailand: IAEC.

Sivarajan, S., M. Maharlooei, S.G. Bajwa, and J. Nowatzki. 2018. Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. *Soil & Tillage Research*, 175: 234–243.

Taylor, H.M., and H. R. Gardner. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Science*, 96(3): 153–156.

Van den Akker, J. J. H., J. Arvidsson, and R. Horn. 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil and Tillage Research*, 73(1-2):1-8.