Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Regression Analysis and Empirical Relationships for Predicting the Penetration Characteristics of Mechanized Tillage Implements in South-East Bioclimatic Region of Nigeria

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ARTICLE INFORMATION

Article history:
Received 12 Sep, 2020
Revised 14 Nov, 2020
Accepted 16 Nov, 2020
Available online 30 Dec, 2020

Keywords:
Regression
Empirical relationships
Tillage
Implements
Penetration resistance

ABSTRACT

A regression analysis was conducted to obtain the empirical relationships for predicting the penetration characteristics of some mechanized tillage implements in south-east bioclimatic region of Nigeria. A Massey Ferguson tractor of model MF 430E was used for the study and the implements studied include the disc plough, harrow, ridger and the rotovator. Results obtained from the developed regression equations showed that plough had penetration resistance of 5.38 kN/cm^3. While harrow, ridger and rotovator operations respectively recorded penetration resistances of 3.48, 1.97 and 1.53 kN/cm^3. The prediction error for the tillage implements range from 2.68 to 11.39% with root mean square error varying from ±1.64 to ±3.37. The comparison of the predicted results with the experimental results revealed that the regression equations did not under-predict the experimental results, though slightly higher, but the prediction errors were within tolerable limit. Furthermore, from the root mean square error analysis, the errors were within acceptable limit of ±5%. The coefficient of determination R^2 for the regression equations developed for predicting the various penetration characteristics of the implements range from 0.7979 to 0.946 which indicates high degree of correlation between the dependent and independent variables and that the equations were adequate for the prediction of the penetration characteristics of the implements.

1. INTRODUCTION

Soil penetration is the measure of the ease with which an object can be pushed into the soil (Bradford, 1986). According to Al-Hashem (2004), it is a way of examining the strength of the soil. Campbell and Henshall (1991) noted that the most common indicators used to examine soil strength or penetration resistance in tillage operations are bulk density and penetrometer resistance. Herrick and Jones (2002) used cone indices to characterize available soil compaction, resistance to growth and/or penetration of plant root, and tillage effects, wheel traffic effects and hard pan resistance into the soil. Bradford (1986) however, related the resistance the soil offers to the penetrometer in penetrating the soil to root penetration or growth, crop yield, and soil physical features descriptive of tilth.

According to Zhang (2001), soil resistance to penetration is dependent upon the physical features of the equipment (such as, height, diameter, and angle of penetration), along with soil characteristics (such as moisture or water contents, bulk density, texture, shear strength, organic matter, and particles surface roughness. Ehlers et al. (1983) noted that mechanical impedance (resistance) of soil increases as bulk density increases and moisture content decreases. Bradford (1986) observed that strength in various horizons of soil can restrict the growth of plant root and their development even if moisture content is at field capacity, evidently soil strength increases as water dries from the soil. In like manner, it affects the workability of the soil by restricting the tilling ability of the tillage implements. Gregory (1994) posited that, the plant roots have to exert enough vertical penetration pressure which may range from 0.7 to 2.5 MPa, however depending on the type of crops to combat the penetration resistance of the soil. According to Franzen et al. (1994), Penetration resistance generally increases with depth because of the increase in magnitude of friction of the shaft of the equipment and the soil. Maurya (1993) reported that, soil strength increased with depth of soil while Saber and Mrabet (2002) stated that, maximum bulk density and soil strength was found in the upper 30 cm in no-tilled soils than deeply tilled ones. Busscher et al. (2000) studied the effective effects of deep soil tillage (in fall and in spring) compared with surface soil tillage (i.e., disked and undisked) on resistance to penetration and yield of wheat and soybean. They discovered that, disking sufficiently compacted the soil higher than it loosened it, having 60- kPa higher average profile soil cone indices than undisked soils. Cavalieri et al. (2006) noted that, the soil resistance to penetration was higher on the no-tillage soil than minimum tilled soil using chiseling and conventional tillage with moldboard plow and disking, while the latest implement reported the minimum penetration resistance

Tillage operation affects both soil resistance to penetration and its related indicators like moisture content and bulk density/compaction; however, because of differences that exist in the physic-mechanical properties and or conditions of soils it is imperative therefore, to ascertain the penetration characteristics of different tillage implements. According to Oduma et al. (2019), development of empirical model is an essential and simple way of assisting the farmers, farm managers and other users of agricultural machinery both at subsistence and commercial level in assessing and predicting the possible performance capabilities of farm machinery. This is to enable them make proper selection of the equipment based on soil type/conditions and season of operation before purchasing and/or engaging any machine to work. They added that, this will go a long way to reduce failures, unnecessary break down, mismatching of implement to prime movers, minimize fuel consumption (energy loss), reduce cost and generally maximize production and profit. The objective of this study is to conduct regression analysis and develop some empirical relationships for predicting the penetration resistance of some selected tillage implements in South-East bioclimatic region of Nigeria, to enable farmers in the area assess and make proper selection of the tillage implements based on soil type/conditions to avoid unnecessary breakdown/failures, minimize cost and wastage of energy during operation.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Machine and apparatus

A Massey Ferguson tractor of model MF430E and capacity 55.2 kW, with 3- point hitch systems was used for the study. The apparatus used include:

i. An Electric Oven of Model n30c Gen Lab Wideness: used to determine the moisture content of the soil
ii. Mechanical Soil Sieve: used for soil textural class (soil type) test
iii. A weighing balance: used to measure the weight of soil samples during the tests
iv. A Proctor Needle Penetrometer: used to measure the penetration resistance of the soil
v. A Standard Proctor Hammer: used to blow the soil for compaction
vi. A Cylindrical Mold: used as container for soil compaction

2.1.2. The experimental site

The experiments were conducted at five different locations, where the dominant soils in the study area are located. The experimental sites have an average area of 8100 m^2 each. The land area was divided into four units of 45 x 45 m^2 each for random observations. Each unit was separated by a distance of 2.5 m from the other to avoid interaction between the plot borders and to be equally used as head lands for turning and commencement of the experimental operations.

2.1.3. Soil type classification of the study area

The soil classification of South east is as shown in the soil map (Figure 1) recorded by Obinna et al. (2013). According to the map different soils such as clay-loam, concretionary clay, loamy-sandy, sandy, sandy- clay and sandy-loam exist in the area; but the three dominant soils in the area as observed in the map are clay-loam, loamy-sandy and sandy-clay soil. This study was based/conducted on these three dominant soils of the area according to Oduma et al. (2019).

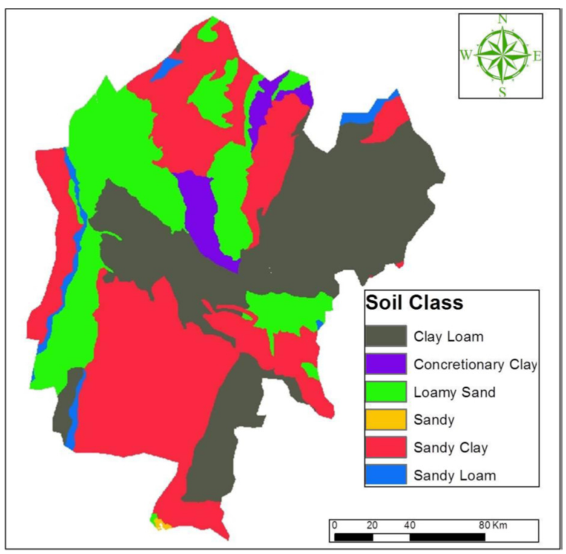

Figure 1: Soil map of south east zone (Obinna *et al*, 2013)

2.2. Methods

2.2.1. Determination of soil moisture content

The oven-dry method of moisture content determination was used to determine the moisture content of the soil samples in the various sites used for the study (Murthy, 2012). The weight of initial samples of soil (wet soils) collected from the site and the weight of oven-dry samples of the same soils (dry soils) was determined in the laboratory and the moisture content was evaluated from Equation 1.

$$M_C = \frac{Ws - Ds}{Ds} \text{ x } 100\% \quad (1)$$

Where:

M_C = moisture content of the soil (%)
W_S = weight of wet soil (initial soil sample) (kg)
D_S = Wight of oven-dry soil (kg)

2.2.2. Determination of soil textural class

The mechanical soil analysis method was used. In the process, a freshly tilled soil free from gravel, stones, plant roots/stumps and organic matters was collected with an air tight container for a quantitative determination of the particle sizes (sand, silt and clay) in the laboratory. The soil sample was properly oven-dried at a temperature of 105 ^oC. The total weight of the soil sample was accurately measured; and was passed through a series of mechanical sieve with mesh of different sizes ranging from 0.002 to 2.0 mm diameter. The weight of the contents of each sieve after mechanical shaking was determined separately and expressed as a percentage of the initial weight of the fine sample; and the textural class of the soil was finally determined using the textural triangle (USDA, 2010).

2.2.3. Determination of soil penetration resistance

The soil resistance to penetration was determined before tillage and after the various tillage operations. For each measurement, the penetrometer was operated by placing the cone on the soil surface with the shaft in vertical position and the base of the cone well placed on the soil surface. While the penetrometer is in position, the cone is pressed into the soil at the rate of 2.5 cm/sec, until it (the cone) is completely buried. This penetration is recorded as zero blows. The slide hammer is raised and dropped to a known number of times depending on the soil strength until a given depth (an arbitrary depth of 8cm was chosen) was achieved. The total blows to reach this desired depth was recorded and the cone index was determined (Equation 2). Thereafter, the penetration resistance was evaluated from Equation 3 (Alnahas, 2003). The cone index of the soil was determined from the expression suggested by Macmillan (2002) as follows:

$$C.I. = \frac{Force\ on\ cone}{Base\ area\ of\ the\ cone} \quad (2)$$

The cone used has base area of 3.226 cm^2
Force applied on the cone = pressure on the penetrometer (0.408 kPa) multiplied by the number of blows

$$P_R = C.I \times \text{Base area of cone} \quad (3)$$

Where:

C.I. = cone index (kPa)
P_R = penetration resistance (kN/cm^2)

2.2.4. Development of empirical regression equations

The data obtained from the study were subjected to regression analysis and empirical regression equations for predicting the implement penetration characteristics at different moisture content levels were developed using trend line of exponential regression tool.

2.2.5. Determination of the adequacy of the equations

The adequacy of the equations developed from the study were determined by comparing the results obtained from the experiment with the regression results using percentage error (Equation 4) suggested by Onwualu et al. (1998). Thereafter, the root mean square (RMS) of the error were evaluated using the method adopted by Kothari (2014) to determine the accuracy of the predicted results. The predictions are considered accurate if the RMS errors of the prediction are within the tolerable limit of ±5%. More so, the coefficient of determination, (R^2) will also indicate the adequacy of the model if it is within limit of 0 and 1 (Kothari, 2014).

$$\text{Error} = \frac{\text{Regression Result} - \text{Experimental Result}}{\text{Experimental Resul}} \times 100\ \% \qquad (4)$$

3. RESULTS AND DISCUSSION

Results of this research work are presented in Table 1 – 3. Table 1 presents the moisture content and the penetration resistance offered by the soil to the tillage implements. Results of this Table showed that plough operation with the highest penetration resistance range of 3.67 – 5.53 kN/cm^3 recorded the highest moisture content range from 15.70 – 16.47 % (w.b). This was followed by harrow with the penetration resistance of 2.45 – 3.67 kN/cm^3 at moisture content range from 15.52– 16.39% (w.b). This is also followed by the ridger with penetration resistance range of 1.22 – 2.25 kN/cm^3 at moisture content range from 14.08 – 15.18% (w.b). The least penetration resistance was recorded by the rotovator (1.22 – 1.63 kN/cm^3 at moisture content of 13.51 – 14.76% (w.b). The penetration resistances obtained for the implements fall within the ideal range of soil resistance to root penetration required for root growth resulting from soil bulk density as observed by Arshal et al. (1996). The moisture contents obtained during the tillage operations were lower as compared to the initial moisture content (18.60% w.b) recorded at zero tilled soil. This may be as a result of evaporation due to exposure of the upper layer of the soil to the direct effect of sun rays during and after tillage operations which is in agreement with the findings of Oduma et al. (2019). Furthermore, the higher moisture content observed for the plough operation as compared to other implements may be attributed to high compaction effect (which decelerates infiltration rate) associated with plough operation, which is consistence with the observations of Salokhe and Shirim (1992).

Table 1: Penetration resistance of the tillage implements at different moisture contents

Trial	Zero tilled soil		Plough		Harrow		Ridger		Rotovator	
	PR (kN/cm^3)	MC (%)	PR (kN/cm^3)	MC (%)	PR (kN/cm^3	MC (%)	PR (kN/cm^3	MC (%)	PR (kN/cm^3)	MC (%)
1	5.71	17.6	5.30	16.18	3.26	15.52	2.04	14.34	1.63	14.07
2	4.08	17.8	5.53	15.7	3.67	16.39	2.25	14.08	1.63	13.51
3	6.53	20.4	3.67	16.47	2.45	16.30	1.22	15.18	1.22	14.76
Mean	5.44	18.6	4.83	16.11	3.13	16.07	1.84	14.53	1.49	14.11

PR = Penetration resistance; MC = Moisture content (% w.b)

Table 2 shows the results of the empirical regression equations developed from the experimental results for predicting the penetration characteristics of the mechanized tillage implements in south-east bioclimatic region of Nigeria. Results showed that at any given level of soil moisture content, the regression equation that can predict the penetration resistance of the plough operation is $y = 3.1027e^{0.0342x}$. While for harrow operation the penetration resistance can be predicted using the relationship, $y = 2.024e^{0.0337x}$. Then for ridger and rotovator operations, the empirical regression equations that can be used to predict their penetration resistances are respectively, $y = 0.9386e^{0.051x}$ and $y = 1.0876e^{0.0241x}$. The coefficient of determination R^2 for the regression equations developed for predicting the various penetration characteristics of the implements range from 0.7979 to 0.946 which indicated high degree of correlation between the dependent and independent variables (Kothari, 2014) and that the equations are adequate for predicting the penetration characteristics of the implements.

Table 2: Regression equations for predicting penetration characteristics of tillage implements

Tillage implement	Regression equation	Coefficient of determination (R^2)
Plough	$y = 3.1027e^{0.0342x}$	$R^2 = 0.8268$
Harrow	$y = 2.024e^{0.0337x}$	$R^2 = 0.9460$
Ridger	$y = 0.9386e^{0.051x}$	$R^2 = 0.8665$
Rotovator	$y = 1.0876e^{0.0241x}$	$R^2 = 0.7979$

Y = Penetration resistance (kN/cm^3) and X = Moisture contents (% w.b)

The developed regression equations were validated by comparing its results with the experimental results using percentage error (Table 3). The prediction error for the tillage implements range from 2.68 to 11.39% with root mean square error varying from ±1.64 to ±3.37. This is consistence with the findings of Oduma et al. (2019) for development of empirical regression equations for predicting the performances of disc plough and harrow in clay-loam soil. The comparison of the predicted results with the experimental results revealed that the regression equations did not under- predict the experimental results, though slightly higher but the prediction errors were within tolerable limit (±5%) as stipulated by Onwualu et al. (1998). Furthermore, from the root mean square error analysis, the errors are within acceptable limit of ±5% according to Kothari (2014).

Table 3: Comparison of results obtained in the field experiment and regression equation for the tillage implements

Implement	Average moisture content (%)	Experimental penetration resistance of implements (kN/cm^3)	Regression result (kN/cm^3)	Error (%)	RMSE
Plough	16.11	4.83	5.38	11.39	±3.37
Harrow	16.07	3.13	3.48	11.18	±3.34
Ridger	14.53	1.84	1.97	7.07	±2.66
Rotovator	14.11	1.49	1.53	2.68	±1.64

RMSE = root mean square error

4. CONCLUSION

The following conclusions can be made from the present study:

i. Plough operation recorded the highest penetration resistance, followed by harrow, ridger and least penetration resistance was recorded by the rotovator.

ii. The comparison between the predicted results and the experimental results revealed that the models did not over or under- predict the experimental results. The prediction errors were within allowable range.

iii. The coefficient of determination (R^2) for the regression equations developed for predicting the various penetration characteristics of the implements range from 0.7979 to 0.946 which show high degree of correlation between the dependent and independent variables and also indicates that the equations are adequate for predicting the penetration characteristics of the implements.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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