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Soil Forces Prediction on Animal Traction Operation in Bongo District of the Upper East Region of Ghana

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The soil and implement interaction during ploughing can be analyzed through the geometry and working depth of the implement and soil parameters such as shear stress, cohesion and soil internal frictional angle. The objective of the study was to predict the forces that react with the implement parts during ploughing in the three (3) sampled areas in Bongo District. Soil samples were taken at a 30 cm depth. Laboratory tests were performed on them on triaxial, grading and Atterberg limits. The results were used to describe the soil and for the force prediction. There were some field tests to determine tractive efforts, speed of travel and ploughing depth. The three (3) soil types considered were sandy loam, loamy sand and course loamy sand. Food and Agriculture Organization classified the three (3) soil types as Lixisols and the local soil series also put all the soil samples as Tranchera. At the time of ploughing, the densities were ranging from 1.28 to 1.44g/cm^3 and moisture content of 9.43 to 22.96%. The rake angle measured on the animal plough

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was 19^0, and the soil metal frictional angles of the three soil type ranged from 32.355 to 37.129^0 with soil cohesion of 0 kPa for course loamy sand, 2.664 kPa for loamy sand and 56.338 kPa for the sandy loam soil. The resultant (P) forces for the three soil samples; loamy sand, sandy loam and course loamy sand were 0.5551 kN, 0.1024 kN and 0.0106 kN respectively.

Keywords: Soil forces prediction; animal traction; soil internal frictional angle; rake angle; soil metal friction angle.

1. INTRODUCTION

The importance of soil cannot be overlooked, because it is the reservoir of nutrients and water for plants growth and development. Soil plays an important role in nutrients recycling. It has a wonderful way of absorbing nutrients and transforming them into usable form for plants. It is a home for most organisms, holds water for plants and filters dirt from water and air making them safe for living things [1]. Tillage is a mechanical modification of soil structure to create soil conditions for seed germination and development. It is considered the major farm operation due to its energy requirements. Tillage is achieved by tillage implement hitched to a power source. This power source can be human, animal or machine. A mould board plough is mostly used by farmer as a primary tillage tool [2]. The draught forces on tillage implement are influenced by soil conditions and operating speed. These conditions are soil type and condition, soil moisture content and ploughing depth among others [3]. In clay soils, implements have greater draught forces as compared to the loam and sandy soils. In special range of moisture content, implements have less draught and out of this range, they may have higher draught. Tillage depth, width, geometry and stability arrangement of implements and forward speed are parameters that may have effect on draught [4].

Most research on draught forces involve different formulas and equations to compute draught forces. These studies however provide data on soil forces, but these are time consuming and labour intensive. Sensing equipment are used to determine the soil strength and soil deformation under the application of various types of tool working conditions [5]. The energy requirement of an implement is the force needed to pull the implement through the soil with a specific speed. Draught force of an implement is the force needed to pull it through the soil [6]. Implement weight, size, type of soil, moisture content of the soil and others factors need to be considered before selecting an implement to a power. There is the need for deeper understanding on the factors that influence draught force and the mechanisms in which tillage implement operate for better selection of implement to a given power unit [7].

Factors that influence draught force include depth of plough, implement width and type, soil type, and speed of travel, soil shear, soil-metal friction coefficient and implement geometry [8]. Information on the horizontal forces is an added advantage in selecting a right implement for a power unit [9]. In selection of tractors and implement farmers depend on their knowledge and experience. Large numbers of imported chisel ploughs are commercially available in local markets of Saudi Arabia. However, there is little information available from the manufacturer on the benefits associated with their design aspects. Accordingly, the knowledge of the effect of chisel ploughs design aspects on horizontal and vertical force (the measure of the ground engaging tool's ability to hold itself at the given ploughing depth) is important in guiding local manufactures to improve the design of chisel ploughs [10].

Whether conservation tillage practice performs better than the long-practiced traditional tillage practices in terms of improvement of edaphic, yield influencing characters of the specific, and unearth soil-water-plant ecosystem of the region is still unknown. As the conservation tillage practices have been reported to manipulate soil positively, they could also be a solution of poorly managed soil condition in the region of rice-wheat cropping system. Soil composition is the key property of soil that determines how it will respond to the effects of tillage operation. Tillage brings great disturbance to soil (physically, biologically or chemically). The composition of soil determines the structure, how it can absorb and conduct water and the amount of air space in the soil. Soil living organisms improve soil structure by the activities in the soil. The effect of tillage on soil property depends on its composition [11, 12,13]. Machines use for tillage operations exert mechanical stresses on the soil destroying soil structure. This is serious especially when they are used on soil that is too wet. It leads to smearing and compaction of soil.

This is because the applied force exceeded the strength of the soil, therefore structure failure.

Tillage operations should generate a favourable soil structure in terms of water, nutrients, oxygen, and temperature. However, soil behaviour changes according to its physical properties. Consequently, the variability in soil mechanical response makes it a difficult task to determine adequate parameters for tillage tools [14]. The proper design and selection of soil-engaging tools to achieve desired soil tilt depends largely on the mechanical properties of the soils. Pattern failure of soil plays an important role in obtaining a better understanding of the mechanical properties of soils under varied soil and tool conditions. The variation in soil failure patterns can be attributed the variations of mechanical behaviour of the soil [15].

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Bongo District, located in the Upper East Region of Ghana. It lies between longitudes 10^0 57' 28" N and latitude 0^0 48' 29" W. The district covers a land area of 495.5 km^2. It shares border with Nabdam District to the east, Bolgatanga Municipal to south, Kasena Nankana District to the west, and Burkina Faso to the north. The population of Bongo District is 84,545 representing 8.1 % of the region's total population. Females constitute 52.4 %, while males represent 47.6 %. Of the employed population, about 72.6 % are engaged as skilled agricultural, forestry and fishery workers [16].

The Bongo District is noted of its rocky nature; hence, the entire underlying area of the district is granite rock. These rocks outcrop, so one can see heaps and mountains of rocks when walking through the district. The soil is known to be productive because it is rich in Phosphate and Potash content. Intensive farming practices are carried out on the land due to the high population density of the area, making erosion common. The soils are well drained, friable, and porous, and possess good filth. They support millet, sorghum, groundnuts, rice, soybeans and many others [17].

2.2 Soil Sampling

Soil samples were taken from three (3) different locations at a depth of 30 cm where animal traction operation was carried out. Pickaxe, spade core samplers, tape measure and black polythene were used in collecting the soil into the soil bags for laboratory testing. The soils were air dried before they taken for various laboratory tests including soil texture and structure.

2.3 Tri-axial Testing

Tri-axial test was carried out to study the mechanical behaviour of the soil under different loads. Three (3) samples (loamy sand, sandy loam and course loamy sand) used in this test with each sample tested in three times with different pressures (100 Pa, 150 Pa and 250 Pa. The sample was placed in the compression machine and a pressure plate is placed on the top. The cell was properly set up and uniformly clamped down to prevent leakage of pressure during the test; the end caps were properly sealed. When the sample was setup, water was added and the cell was fitted under water escapes from the beed valve, at the top, which is closed. The air pressure in the reservoir was increased to raise the hydrostatic pressure to the required level. The pressure gauge was closely monitored during the test, and any necessary adjustments were made to keep the pressure constant. The handle wheel of the screw jack is then rotated until the underside of the hemispherical seating of the proving ring, through which the loading was applied, just touches the cell piston. The piston was moved downward by the handle until it just touches the pressure plate on the top of the sample, and the proving ring seating is brought into contact for the beginning of the test. Fig. 1 presents the triaxial testing equipment.

2.4 Force Prediction Procedure

The soil force prediction formulae used by [14] and presented on the following parameters for the draught (H) and vertical forces acting on a tine (narrow tine) were adapted in this study.

$$H = (\gamma d^2{}_c N\gamma + cd_c N_c + qd_c Nq) \times [w + d\{m - \tfrac{1}{3}(m - 1)\}]\sin(\alpha + \delta) \quad (1)$$

$$V = -(\gamma d^2{}_c N\gamma + cd_c N_c + qd_c Nq) \times [w + d\{m - \tfrac{1}{3}(m - 1)\}]\cos(\alpha + \delta) \quad (2)$$

Where $H_t = [(\gamma d^2 N\gamma + cdN_{ca} + qdN_q)w]\sin(\alpha + \delta)$ ....(3)

$$V_t = -[(\gamma d^2 N\gamma + cdNca + qdNq)w]\cos(\alpha + \delta) \quad (4)$$

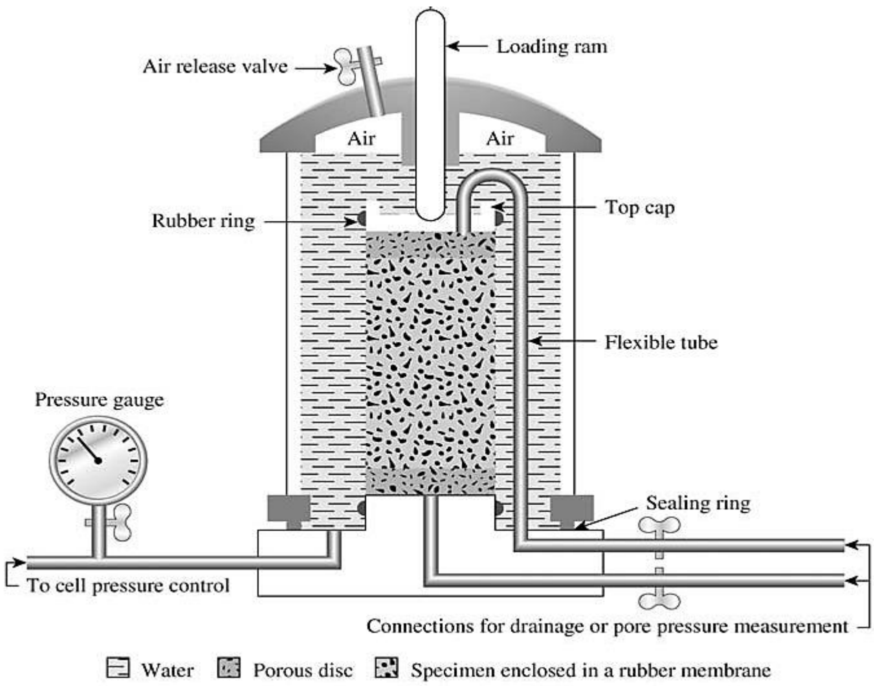

Fig. 1. A Diagram of the Triaxial Test Equipment.
Adopted from [18]

Where: P is the resultant force, H_t and V_t are horizontal and vertical forces, d and w are blade depth and width respectively, α the is rake angle, δ is the angle of soil-metal friction and $\gamma$are soil cohesion and density respectively, q is the soil surcharge (considered zero in this work) Nca, Nγ, Nq, dimensionless values.

2.5 Soil Internal Friction (∅)

According to [19], the values of ∅ ranged from 35 – 40^0 for sandy loam soil, 34 – 48^0 for sandy soil , and 35 – 38^0 for loamy soil . So, 35^0 was used for sandy loam and loamy sand whilst 34^0 was used for gravelly loamy soil in the computation. The values for the dimension less parameters (Nγ, Nc, and Nq) were obtained for the various soil samples with the help of the rake angle measured on the field, soil internal friction and the chart according to [14]. Equations 5 to 7 were used in computing the values for soil internal friction.

$$N\gamma = N\gamma\delta = 0(\frac{N\gamma\delta=\emptyset}{N\gamma\delta=0})^{\frac{\delta}{\emptyset}} \quad (5)$$

$$Nq = Nq\delta = 0(\frac{Nq\delta=\emptyset}{Nq\delta=0})^{\frac{\delta}{\emptyset}} \quad (6)$$

$$Nc = Nc\delta = 0(\frac{Nc\delta=\emptyset}{Nc\delta=0})^{\frac{\delta}{\emptyset}} \quad (7)$$

Where: Nc, Nγ, and Nq are dimensionless values, Soil internal friction**al** angle(∅) α, is the rake angle, δ is the angle of soil-metal friction c and γ are soil cohesion and density respectively, q is the soil surcharge (considered zero in this work). Data were processed with Microsoft excel and results presented in graphs and tables.

2.6 Field Test

Soil samples were taken from three (3) different locations where animal traction operation is carried out at a depth of 30 cm as the animal traction was performed at 30 cm depth. Pickaxe and the spade were used in collecting the soil into the soil bags for laboratory testing. Three sets of bullocks of average age 7 years were used for the ploughing. Three (3) portions of an acre land (4,000 m^2) were measured on each location where soil sample is taken using the tape measure, the three (3) sets of animals were used to plough one portion in each location. Time taken to complete the portion of land was measured, rake angle and the rapture distance were also taken. After ploughing, sample measurements of the depth of cut and the width of cut were taken on the fields. Bulk densities and moisture content of the soils was determined on the fields before and after ploughing. A stopwatch or clock was used in timing them as they plough, with their usual harnessing equipment, tape measure, hoe, mouldboard plough, and Global Positioning System (GPS) was also used to take coordinates of the animal traction areas.

3. RESULTS AND DISCUSSION

The findings of the study were presented and discussed in the proceeding sections namely texture of the soil in the area, Atterberg limits, Tri-axial and work rate.

3.1 Texture of the Soil

The mineral particles of the soil in the study area presented in Table 1.

The combined clay and silt fractions are higher for sandy loam, followed by the gravelly loamy sand and then loamy sand. Food and Agriculture Organisation (FAO) classified the three soil samples as lixisols and the local series is trachera. This soil series is light brownish, grey, slightly humus and crumbly loamy sand underlain by loose light yellowish brown loamy coarse sand. The soil is loose, coarse texture and easy to cultivate. However, it is also easily eroded and poorly supplied with nutrients [20]. This description is a true reflection of the soils in Bongo District.

3.2 Atterberg Limits

The Atterberg limits results are presented in Table 2.

The plastic and liquid limits both depend on the nature of clay, colloidal materials and cations saturation and the amount of clay content in the soil. Increased in percentage of clay leads to higher plastic limit then increase in the plasticity index. On the other hand, decrease in clay content also leads to decrease in liquid limit thereby lowering the plasticity index [21]. The nature of clay minerals affects plasticity index too. Those clay minerals that have platy or sheet like structure exhibit plasticity. For example, Quartz and feldspar whose crystal are not made linked tetrahedral are non-plastic. On the other hand, kakolinite biotite and others whose crystals lattices are made up of sheets are plastic. Furthermore, the type of clay mineral has great impact on water absorption by colloidal substance. The nature of cations also affect plasticity index. For example, Na saturation decreases plastic limit thereby increasing plasticity index while K saturation lowest the plasticity index by lowering liquid limit. The lower the plasticity index (PI) the lesser the clay or colloidal substance of the soil sample [22]. In view of this the result shows that the colloidal substance content in the sand soils is more than that of the sandy loam and loamy sand soil sample. Also, the combine percentages of silt and clay content of the three soil samples has great influence on the plastic values.

3.3 Tri-axial Results

Table 3 presents the summarised results for the tri-axial test experiments with the values obtained from the Mohr Circle.

From Table 3, the sandy loam with its higher value of cohesion of 56.338kpa. On the other hand, it has the lowest angle (32.355^0) of soil internal friction as compared to the others. This corresponds to the highest value of soil cohesion (c). The loamy sand sample is second with higher cohesion. This made it to have second lower angle of soil internal friction to the sandy loam sample. Course loamy sand has the lowest value of cohesion and the highest value of the angle of soil internal friction. Hence, it is a soil with less cohesiveness.

Table 1. Textual Class of Soils from Experimental Fields

Sample No.	% sand	% silt	% clay	% gravel	Textual class	FAO Name	Local Series
1	59	30	11	0	Sandy loam	Lixisols	Tranchera
2	85	8	2	5	Loamy sand	Lixisols	Tranchera
3	58	11	2	29	loamy sand	Lixisols	Tranchera

Table 2. Atterberg limits

Soil Sample	Liquid limit (W_L)	Plastic limit (W_p)	Plasticity index (I_p)
Sandy loam	22.76	14.81	7.95
Loamy sand	21.05	13.45	7.62
Course loamy sand	21.52	12.79	8.73

Table 3. Results from Tri-axial Test

Sample ID	Cell Pressure (Pa) (Σ_3)	Deviator Stress (Σ_2)	σ_1	Cohesion (c)(kPa)	Angle of internal friction (°)
Sandy loam	100	399.2	499.2	56.338	32.355
	150	603.91	753.91		
	250	762.51	1012.51		
Loamy sand	100	309.52	409.52	2.664	36.193
	150	427.2	577.2		
	250	736.83	986.83		
Loamy sand	100	251.48	351.48	0	37.129
	150	341.64	491.64		
	250	777.16	1027.16		

Table 4. Soil Conditions at the time of ploughing

Soil Parameters	Sandy loam	Loamy sand	Course loamy sand	Average	Standard deviation
Wet bulk density(g/cm^3)	1.58	1.57	1.47	1.54	0.06
Dry bulk density(g/cm^3)	1.44	1.28	1.34	1.35	0.08
Moisture content (%)	10.40	22.96	9.43	14.26	7.55

The physical properties of soils are helpful to both agricultural and civil engineering problems. They aid in understanding soil bearing capacity, stability issues, lateral pressure, and internal resistance to dynamic and static loads. Soil parameters such as c and ϕ, etc are vital in determining solutions to practical problems in an area. Sustainable operations heavily rely on knowledge of soil physical properties. Furthermore, it is noted that the internal friction of soil generally decreases with a decrease in plasticity index [21]. Within soil particles, there exists internal forces that can resist failure [23]. These forces are soil cohesive strength (c) and angle of soil internal friction (ø). The force is more pronounced in high cohesive soil (high value of c and low value of ø) than cohesive less soil Based on the obtained results, it is observed that loamy sand soils are more cohesive than sandy loamy soils. Course loamy sand soils are less cohesive. This discrepancy influences the force values in the various soil samples. Consequently, cohesive soils exhibit higher forces than less cohesive soils, as evidenced by the calculated forces. This implies that more energy is required to pull a plough through cohesive soil compared to less cohesive soil.

As presented in Table 4, it can be observed that the wet and dry bulk densities are within the acceptable range of density of Agricultural soil for proper crops production.

3.4 Work Rate

The work rate results obtained from the bullocks ploughing trials are presented in Table 5. For the studied soil conditions, the average work rate for bullocks ploughing operation were 158.34 min/ha, 181.36 min/ha, and 170.03 min/ha for loamy sand, sandy loam and course loamy sand respectively. From these results, it can be inferred that due to the cohesiveness of the loamy sand soil, ploughing there was more challenging compared to sandy loam and gravelly loamy sand soils. This finding confirms the assertion that ploughing in cohesive soil is more difficult than in cohesive less soil, as stated by [23].

The computed soil forces show the highest values (0.555 kN) for cohesive soil (loamy sand) and very low values (0.011 kN) in cohesive less soil (course loamy sand), as shown in Table 6. This indicates that more energy is required to pull the plough through the loamy sand compared to sandy loam and gravelly loamy sand. This correlation is evident when comparing the work rate results or the area ploughed. Knowledge of soil forces informs farmers' decisions regarding which soil-engaging implement to apply in a particular soil [5]. Additionally, understanding these forces within the draught team can enhance comprehension of necessary adjustments to the harness and implement, and aid in evaluating the implement. This adhesive force provides information on the wear and tear of the implement part as they move through the soil [14].

Table 5. Work rate

Parameter	Soil Type														
	Course Loamy Sand					Loamy sand					Sandy loam sand				
	1	2	3	Ave.	stdev	1	2	3	Ave	Stdve.	1	2	3	Ave	Stdev
Depth of cut (cm)	12.4	11.8	10.3	11.5	±1.06	15.3	12.4	12.4	13.3	±1.61	13.2	10.1	11.3	11.5	±1.58
Width of cut (cm)	32.3	28.8	29.3	30.1	±1.90	22.3	33.1	23.3	26.3	±5.99	30.6	36.8	28.8	32.1	±4.16
Area ploughed (m^2)	660	540	580	593	±61.01	560	725	450	588	±138.41	825	570	580	661	±142.31
Time taken(min)	10	10	8	9.3	±1.55	10	12	9	10.3	±1.53	12	11	9	11	±1.00
Work rate (min/ha)	152	185		158	±24.17	179	166	200	181	±17.41	145	193	170	170	±23.97

Table 6. Soil dynamic properties and forces prediction

Parameters	Sandy loam	Loamy sand	Course loamy sand	Average	Standard Deviation
Implement width (m)	0.23	0.23	0.23	0.23	0
Average depth of cut (m)	0.13	0.12	0.12	0.12	±0.01
Average width of cut (m)	0.30	0.26	0.32	0.29	±0.03
Dry bulk density (g/cm^3)	1.89	1.82	1.94	0.88	±0.06
Soil-metal friction angle (^{0})	36	32	37	35	±2.65
Soil internal friction (^{0})	35	35	34	34.67	±0.58
Rake angle (^{0})	19	19	19	19	0
Soil rapture-depth ratio	2.97	3.03	3.52	3.17	±0.31
$N\gamma$	2.53	2.24	2.51	2.43	±0.16
Nc	5.10	1.13	5.28	3.84	±2.35
Nq	1.76	4.56	1.97	2.76	±1.56
Depth / width	0.44	0.44	0.36	0.41	±0.05
Soil force (kN)	0.102	0.555	0.011	0.222	±0.291

4. CONCLUSION

It was revealed that the loamy sand in the study area is highly cohesive, as it recorded a high cohesion value of 56 kPa and low angle of soil internal friction of 32^0. The sandy loam recorded low cohesive value of 2.66 kPa and high angle of soil internal friction of 36^0. However, the course loamy sand is cohesiveless as it recorded a cohesion value of 0 kPa and high angle of soil internal friction of 37^0. Additionally, at optimum moisture content, sandy loam and course loamy sand have higher maximum dry densities compared with the loamy sand.

It was also found that the forces acting on the animal plough engaged in the soil for the three soil types; loamy sand, sandy loam and course loamy sand were 0.5551 kN, 0.1024 kN and 0.0106 kN respectively. With these results it can be concluded that, it will be more difficult to work with the loamy sand soil than the sandy loam and sand soils. This is because there is high amount of clay in it than the other soils hence greater force exerted compared with sandy loam and the gravelly loamy soil. It can be concluded that, soils with high clay materials or content have higher values of cohesion and exert higher forces to machine parts during ploughing. That is why heavy soils are mostly difficult to work with, because they contain high amount of clay materials hence cohesion values and at the end exert higher forces during ploughing. The general conclusion of the forces calculated above, the resistance of soil against the movement of the implement in them is minimal. This accounts for the dominance of manual farming operations and animal power. There are very few tractor operations in the area because the soil is easy to work with.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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