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Prediction of Traction Requirements and Slippage Percentage for Three Plow Types under Various Operational Conditions

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Abstract: This study aims to predict the traction requirements represented by draft force and slippage percentage under different soil moisture levels (7, 14, 22, and 28%), using three plows namely: - moldboard plow, chisel plow and disk plow, Three tillage depths (15, 20, 25 cm) and three forward speeds (1.83, 3.06, 5.22 km/h) were tested in clay loam soil in Qurna, Basra. Data were analyzed using Design Expert software to model draft force, slippage, and tractor performance. Based on the results obtained, it is found that the draft force increased by 62.84% and 29.05% when the depth was increased from 15 to 25 cm and the speed from 1.83 to 5.22 km h^{-1} respectively. Meanwhile, the slippage increased by 78.27 and 54.79% when the depth was increased from 15 to 25 cm and speed from 1.83 to 5.22 km h^{-1} respectively. Moreover, soil moisture at 14% gave the lowest draft force and slippage, reaching 10334 N and 12.39%, respectively, compared to other moisture levels. The results show that the use of the disk plow recorded the lowest draft force and slippage of 9966 N and 15.90%, while the use of the moldboard plow led to an increase in the draft force and slippage as it reached 12671 N and 19.02% respectively. The data analysis shows that the developed model has a good ability for prediction compared to the field data, as the coefficients of determination of the draft force and slippage are 0.9531 and 0.9480 respectively.

Keywords: Draft force, Forward speed, Plowing depth, Prediction, Slippage, Soil moisture content.

Introduction

The draft force is the force required to pull agricultural machinery towards the power source and a opposite to the direction of movement of the agricultural tractor. Understanding draft force is necessary for assessing the ability of the tractor to pull the tillage machines draft force is affected by many factors, including the type of tillage machine, working width, tillage depth, and the forward speed of the tractor, as well as soil characteristics such as texture and moisture (Zhao *et al.,* 2022). Many studies discussed that the draft force is affected by the depth of tillage and the forward speed of the tractor, as they found that the draft force increases with increasing the depth of tillage and also increases with the increase in the forward speed of the tractor (Zhao *et al*., 2022; Almaliki, 2018, Nassir *et al.,* 2024). Almaliki (2017) found that the draft force increased by 74% with the increase in the forward speed of the tractor. The type of plow also impacts draft force, as the moldboard plow gives a higher draft force compared to the chisel plow and the disk plow, and this is due to the nature of the work of the moldboard plow, as it works to cut, raise and turn the soil slice, which requires a higher draft force than those of other plows (Ranjbarian *et al*., 2017).

Slippage is defined as a reduction in the tractor's speed compared to its theoretical velocity (ASAE, 2003). Slippage is one of the important indicators to evaluate the performance of the mechanical unit, as the Slippage should not exceed 15%, because the increase in slippage from this percentage causes loss of draft power, increased fuel consumption, and also causes deformation in the surface layers of the soil and its compaction, which negatively affects the growth and production of the plant, so it is necessary to provide appropriate conditions to work at the lowest permissible slippage percentage (Mamkagh, 2019). Several studies show that the plowing depth and forward speed have an effect on the slippage percentage, where it increases with the increase in the forward speed of the tractor and the plowing depth. It is due to the increased load on the tractor with the increase in depth and speed as a result of the increased strength of the soil with the increase in depth. In addition, the chance of adhesion between the tractor wheels and the soil is reduced by increasing the speed, which increases the slippage percentage (Tayel *et al*., 2015). Almaliki *et al*., (2021) found that the slippage percentage is a key criterion for evaluating fuel consumption and tractor performance in the field. The type of plow has slippage which increasing using a moldboard plow compared to chisel and disc plows. Since the moldboard plow requires higher draft force, this leads to reduce the actual speed thereby increases slippage (Aziz *et al.,* 2013). Primary and secondary tillage are essential operations for seedbed preparation. Primary tillage machines, such as moldboard, a chisel and a disc, are the most widely used in soil tillage operations. However, the tractor should be suitable with the tillage machines to ensure high operational efficiency in the field. (Wandkar *et al*., 2013).

The tillage practices are affected by many factors, including soil properties, texture, type of plow and operating conditions. However, the most influential factor in tillage is soil moisture, which affects the degree of soil fragmentation as well as energy requirements and slippage. (Nassir, 2018). Many studies have indicated that the best soil moisture level for plowing is 14-18%, however, this range cannot always be achieved due to the different weather conditions during the seasons of the year, such as high temperatures, rain and wind. The slippage percentage is affected by soil moisture content, many studies have found that the slippage percentage increases as the moisture content of the soil increases. Also, increasing soil moisture causes deterioration of other mechanical indicators due to the increased cohesion coming from the water films between soil particles, which increases the strengthened soil, and thus increases the traction force and the slippage percentage. (Amponsah *et al*., 2014). However, high moisture at certain levels leads to improved performance indicators and reduces fuel consumption (Al-Suhaibani *et al*., 2015).

The process of testing tillage equipment under different field conditions and multiple operating conditions is time-consuming and considered an expensive and stressful process. Modeling has become easier and can be used to avoid such problems, so researchers have turned to using analytical methods to predict tillage requirements. Intelligent computing technologies and Forecasting programs have been used in many disciplines and different scientific research such as neural networks, artificial intelligence, statistics, machine education and fuzzy data to address problems related to field work and technical operations management in various types of engineering, medical and other sciences (Kamilaris & Prenafeta-Boldú, 2018; Monjezi, 2021; Monjezi & Hosseinzadeh, 2021; Salim *et al.,* 2022). Godwin *et al*., (2007) Conducted a study to provide a mathematical model to predict the draft force of a moldboard plow based on some engineering designs of the plow, the forward velocity and the depth of tillage under different field conditions. According to some physical and mechanical properties of the soil, the measured draft force was compared with the draft force obtained from the mathematical models and found that the results predicted by the mathematical model were 2.8% lower than the measured values. Azimi-Nejadian *et al.* (2019) showed that it is possible to predict the draft force for the moldboard plow, according to the conditions of physical soil from moisture and an apparent density (3-22 % and 1.15-1.77 Mg m^{-3}) under the influence of various speeds and depth (0.9-2.25 m s^{-1} and 0.1-0.25 m) where the determination coefficient of the predicted values reached 0.82.

This study aims to find a mathematical model to predict the effect of soil moisture on the traction requirements represented by traction force and slippage of the tractor using three types of plows (moldboard plow, chisel plow, disc plow) under different operating conditions.

Materials & Methods

Experiment Location

The field experiments were conducted in the Qurna district, northern of Basrah Governorate, which is geographically located at 24.8' 56 30◦ N longitude and 27 47◦ '52.0' E latitude, in clay loam soil composed of (27% sand, 34% silt, and 39% clay).

Tractors and Tillage machines

The mechanical work was performed using the Indian-made CASE JX75T tractor (leader) is equipped with a 4-stroke, 4-cylinder engine, running on diesel fuel. It generates traction power with its front and rear wheels (AMF) and its design power is 55 kW (1500 rpm). The Turkish-made MF285g tractor (follower) equipped with a 4-stroke, 4-cylinder engine, running on diesel fuel. It generates traction power with its front and rear wheels (AMF) and its design power is 56 kW (1500 rpm). Three plows were used in the experiment, three-furrow moldboard plow (working width 100 cm), an 11-shank chisel plow (working width 220 cm) and a three-furrow disc plow (working width 100 cm).

Physical and Mechanical Properties of the Soil

The physical and mechanical properties of the soil were measured for each block as shown in Table (1). The bulk density and moisture were measured by taking random samples using the core sampler method and weighing them before drying. The soil samples were dried in an oven at a temperature of 105 °C until the weight became constant. The bulk density was calculated using equation (1). The moisture was calculated using equation (2). The porosity was calculated using equation (3) according to the method described by Black (1965).

$$\rho_b = \frac{M_S}{V}$$

Where:

ρ_b: Bulk density (Mg cm^{-3}).

M_S: Solid particle mass (gm).

V: The total volume of soil and represents the volume of the cylinder (cm^3).

$$Pw = \frac{Mw}{M_s} * 100 \quad \text{............ (2)}$$

Where:

Pw: Percentage of soil moisture based on dry weight (%).

Mw: Soil moisture weight (g).

M_s: Solid particle mass (gm).

$$f = (1 - \frac{\rho b}{\rho s}) * 100 \quad \text{...................... (3)}$$

Where:

f: Total porosity (%).

ρb: Bulk density (Mg cm^{-3}).

ρs: Particle density (g cm^{-3}).

The field (Cone Penetrometer) is used to measure the resistance of the soil to penetration (CI) by applying continuous pressure on the device in a vertical direction to push the cone inside the soil and in three repeats, recording the readings from the device's indicator and then calculated the cone index (CI) in kNm^{-2} from equation (4) as mentioned in ASABE Standards (2009).

$$Cone\ Index(CI) = \frac{Penetration\ Force}{Cone\ base\ area} \dots\dots\dots\dots\dots\dots.(4)$$

Where:

Cone Index (CI): kN m^{-2}.

Penetration Force: kN.

Cone Base Area: m^2.

The electrical conductivity of the soil was measured by deciSiemens m^{-1} (ds m^{-1}) unit in a soil filtrate (1:1) using an EC-Meter type WTW device.

The cohesion of the soil was measured using the Annuals Ring device consisting of a metal tablet with a diameter of 22 cm equipped from the bottom with radial appendages height of 1 cm and equal in dimensions, also it is equipped with a torque meter. The measuring process is performed by pushing the metal disk towards the surface of the soil in a vertical manner to insert the radial appendages, the disk is rotated by the torque meter arm until the soil between the appendage's collapses, and the torque required to cut the soil is measured at the moment of collapse. Experiments ware conducted using different weights (6.85, 9.14, 11.42, 13.98, and 16.27 kg), the weights ware placed on the metal disk and the process was repeated three times. According to the Soil shear stress from equation (5) taken from ASABE Standards (2009).

$$\tau = \frac{3m}{2\pi r^2} \dots\dots\dots\dots\dots\dots\dots (5)$$

Where:

τ: Soil shear stress (kN m^{-2}).

m: Soil shear torque (kN m).

r: Radius of the metal disc (m).

The vertical stress applied to the soil is also calculated from equation (6).

$$\sigma = \frac{Q}{A_1} \dots\dots\dots\dots (6)$$

Where:

σ: Vertical Stress (kN m^{-2}).

Q: Vertical force applied to the soil (device weight + Added weight) (kN).

A_1 : Metal disk area (m^2).

The relationship between soil shear stress and vertical stress was plotted to calculate cohesion and the results are shown in Table (1).

The adhesion and friction angle between the soil and the metal were measured using the SLED TEST. The device weights 0.538 kg and its front part is higher from the soil surface in a curved way to prevent soil accumulation during operation. The experiment was carried out by pulling the metal piece on the surface of the soil and using different weights. The horizontal stress required to pull the metal piece was calculated from equation (7) taken by ASABE Standards (2009).

$$\tau_\alpha = \frac{F_1}{A_2} \dots\dots\dots\dots\dots\dots\dots (7)$$

Where:

τ_α : Horizontal stress (kN m^{-2}).

F_1: The Draft force of the metal piece with weights (kN).

A_2: Area of contact of the metal piece with soil (m^2).

Moreover, the vertical stress applied to the soil is calculated from equation (8).

$$\sigma_a = \frac{Q_1}{A_2} \dots\dots\dots\dots\dots\dots\dots (8)$$

Where:

σ_a : Vertical stress (kN m^{-2}).

Q_1: Weight applied to the soil (device weight + Added weight) (kN).

A_2: Area of contact of the metal piece with soil (m^2).

The relationship between horizontal stress and vertical stress was plotted according to adhesion and the results are shown in Table (1).

Table (1): Physical and Mechanical Properties of Soil.

Transactions	bulk density Mg m^{-3}		Penetration resistance kN m^{-2}		Electrical conductivity ds m^{-1}		Cohesion kN m^{-2}		Adhesion kN m^{-2}
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	
1	1.42	1.44	1700	1800	14.98	14.96	10.70	10.78	**0.0867**
2	1.11	1.25	1200	1333	13.3	7.55	5.34	6.99	**0.1263**
3	1.24	1.28	1066	1133	10.71	7.36	7.71	8.75	**0.1362**
4	1.35	1.45	820	850	3.66	9.03	9.58	9.92	**0.304**

Study Factors

Draft Force

The total draft force of the tillage machine was measured using a Load Cell (H3-C3-3.0T-6B-D55 Model) manufactured by ZIMIC with a maximum load of 3 tons (30 kN). The device was fixed to the rear of the Case JX75T and connected to the front of the MF285G and the gearbox was set to neutral for the Massey Ferguson tractor. The tillage machine was attached the other side of the weight using a thick rope. The MF285g tractor and the tillage machine tied to it were pulled by the tractor Case JX75T. The total draft force was measured during the pulling process and within a longitudinal distance of 10 m. The draft force values were recorded by a laptop computer connected to the weight cell device, and the measurement process was repeated three times for all types of plowing machines used in the experiment considering three speeds (1.83, 3.06, and 5.22 km h^{-1}) and three depths (15, 20, and 25 cm). The draft force was calculated from equation (9) taken from Mckyes (1985).

$F = F_t - R$ ……………. (9)

Where:

F: The Draft force of the tillage machine F_t Total draft force (N).:(N).

R: The Rolling resistance of the tractor MF285G (N), was measured according to the same method as described above but with the plow lifted from the tractor.

Slippage Percentage

The slippage percentage of Case JX75T wheels were calculated during the plowing operating for a distance of 10 m according to equation (10) mentioned by Zoz and Grisso (2003). The theoretical and practical speed of the tractor was measured using the fifth wheel technology installed on the Case JX75T tractor (pic. 1). This technology consists of a wheel with an encoder sensor fixed on it, the encoder sensor contains a gear connected to the fifth wheel gear. The sensor is also connected by wire to the data collecting unit near the driver. The sensor produces 360 pulses for every revolution of the encoder gear, and each pulse represents a distance of 1.32 mm of wheel movement, then through the data collecting unit, the distance and time were calculated to measure the theoretical speed on paved land without plowing and the practical speed in the field during work.

$S= 1-\frac{Va}{Vt} * 100 \ldots\ldots\ldots\ldots (10)$

Where:

S: Slippage percentage (%).

Va: Practical speed (km h^{-1}).

: Theoretical speed (km h^{-1}).

Vt

Picture (1) Fifth wheel

Field Experiments

Field work began with an experiment to determine the moisture levels during plowing, where an area of soil was located and surrounded by soil and then irrigated. Moisture samples were taken every two days to determine soil moisture and its changes over time and the required work levels were determined based on the data obtained. The field was divided into four blocks, each block with an area of 1600 m^2. Each block was irrigated according to the period specified in the first experiment to determine the moisture level, where four moisture levels were used: 7, 14, 22, and 28%. Soil samples were taken to measure the physical and mechanical properties of the soil before plowing. The mechanical work and measurements of the draft force and slippage were carried out using a CASE JX75T tractor pulling an MF285G tractor and the machine attached to it by thick wire. The draft force and the slippage are measured for each moisture level and for three types of plows (moldboard plow, chisel plow, disc plow) at three speed levels (1.83, 3.06, 5.22 km h^{-1}) and three depths (15, 20 and 25 cm) and each experiment were repeated three times. The plowing depth was measured using an electronic ultrasonic technique through an ultrasonic sensor. The distance was calculated using the reflection time (the time of the wave's round trip) using equation (11), meanwhile, the distance between the sensor and the soil surface was determined using equation (12).

The measured distance (md) = (T * V) / 2 .... (11)

Where:

T: Time interval between the transmitted and received wave.

V: Speed of sound (340 m s^{-1}).

To find the tillage depth, the following equation is used:

Tillage depth = DF - DT .... (12)

Where:

Tillage depth: Depth of tillage (cm).

DF: Distance measured on a level paved ground (cm).

DT: Distance measured in the field during plowing (cm).

Mathematical Model

Design Expert software (version 8.0.6.1) was used to develop a mathematical model for traction requirements and slip ratio. A total of 324 tests were conducted under different field conditions. The study included four independent factors: three types of plows (moldboard plow, disc plow, and chisel plow), four moisture levels (7, 14, 22, and 28%), three plowing depths (15, 20, and 25 cm), and forward speed (1.83, 3.06, and 5.22 km h^{-1}), to create reliable models for traction requirements and slip ratio. The effect of these factors on traction requirements and slip ratio was evaluated using the analysis of variance (ANOVA) method. Table (2) shows the ranges of experimental values of the independent factors and their coded values. Design Expert software was also used to select robust and reliable models, with several polynomial models evaluated.

Results & Discussion

Draft Force

Fig. (1) shows the effect of soil moisture and plowing depth on the draft force, and Table (3) shows the effect of study factors on the draft force. It is clear from both Fig. (1) and the statistical analysis data given in Table (3) that soil moisture has a significant impact on the draft force. When the soil moisture is 7% (dry state) the draft force reaches 10834 N, however it decreases by 4.61% when the soil moisture is increased to 14%. Although when the moisture increases to 22 and 28% the draft force also increases by 5.54 and 11.08% due to the increase in soil cohesion resulting from water films, as well as the increase in soil adhesion to the plow, which increases the soil resistance to the plow, hence, the draft force increases. This result is consistent with what Kim *et al.*, (2021) reached, where observed an increase in the draft force with the increase in soil moisture. It is also noted from Fig. (1) and the variance analysis table that plowing depth has a substantial effect on the draft force, as the draft force increases with increasing the plowing depth from 15, 20 to 25 cm, reaching 8333, 11575 and 13570 N for depths of 15, 20 and 25 cm, respectively. The reason behind this is due to the increase in soil strength by increasing the depth of tillage as a result to the increased bulk density, cohesion and resistance to penetration by increasing depth, which increases the resistance of the soil to tillage and thus increases the draft force with increasing depth, and these results are consistent with Zhao *et al.*, (2022). The results of the ANOVA table also indicated that the effect of the interaction between soil moisture and depth is insignificant on the draft force.

Fig. (2) shows the effect of soil moisture and the forward speed of the tractor on the draft force. It is noted from the analysis of the variance table (Table 3) that the forward speed has a serious effect on the draft force. The draft force increases with the increased in the forward speed of the tractor from 1.83 to 5.22 km h^{-1} by 29.05%, and the values of the draft force were 9824, 10977, and 12678 N for speeds of 1.83, 3.06, and 5.22 km h^{-1}, respectively. This is due to the increased fragmentation of the soil by the plow with the increased in speed, which increases the resistance of the soil to separation and thus increases the draft force. These results are consistent with what Muhsin (2017) and Almaliki (2017) reached, where Almaliki (2017) observed an increase in the draft force by 74% when the speed increases from 0.39 to 1.56 m s^{-1}. The results of the statistical analysis in Table (3) indicate that there is no major effect on the interaction effect between soil moisture and the forward speed of the tractor on the draft force.

Table (2) Ranges of the independent parameters for predicting Draft fore and slippag

Name	Type	Minimum	Maximum	Coded Values	Mean	Std. Dev.	
Moisture Content	Numeric	7.00	28.00	-1.000=7.00	1.000=28.00	17.75	7.95
Tillage Depth	Numeric	15.00	25.00	- 1.000=15.00	1.000=25.0 0	20.00	4.08
Tractor Speed	Numeric	1.83	5.22	-1.000=1.83	1.000=5.22	3.37	1.40
Plow Type	Categoric	Moldboard Plow	Disk Plow			**Levels**	3

Table (3): ANOVA Table showing the effect of study factors on draft force.

Source	Sum of Squares	df	F- Value	p-value Prob > F
Model	2.497E+009	14	365.59	**< 0.0001**
A-Moisture Content	8.965E+007	1	223.14	**< 0.0001**
B-Tillage Depth	1.481E+009	1	3686.03	**< 0.0001**
C-Tractor Speed	4.443E+008	1	1105.96	**< 0.0001**
D-Plow Type	4.117E+008	2	512.43	**< 0.0001**
AB	0.000	1	0.000	**1.0000**
AC	0.000	1	0.000	**1.0000**
AD	0.000	2	0.000	**1.0000**
BC	1.602E+006	1	3.99	**0.0467**
BD	3.799E+006	2	4.73	**0.0095**
CD	6.190E+006	2	7.70	**0.0005**

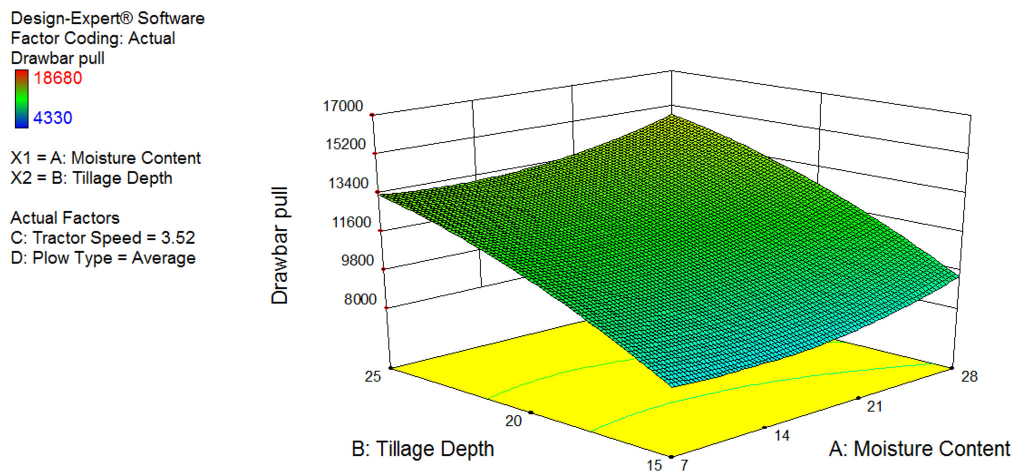

Fig. (1): Effect of tillage depth, soil moisture and their interaction on the draft force.

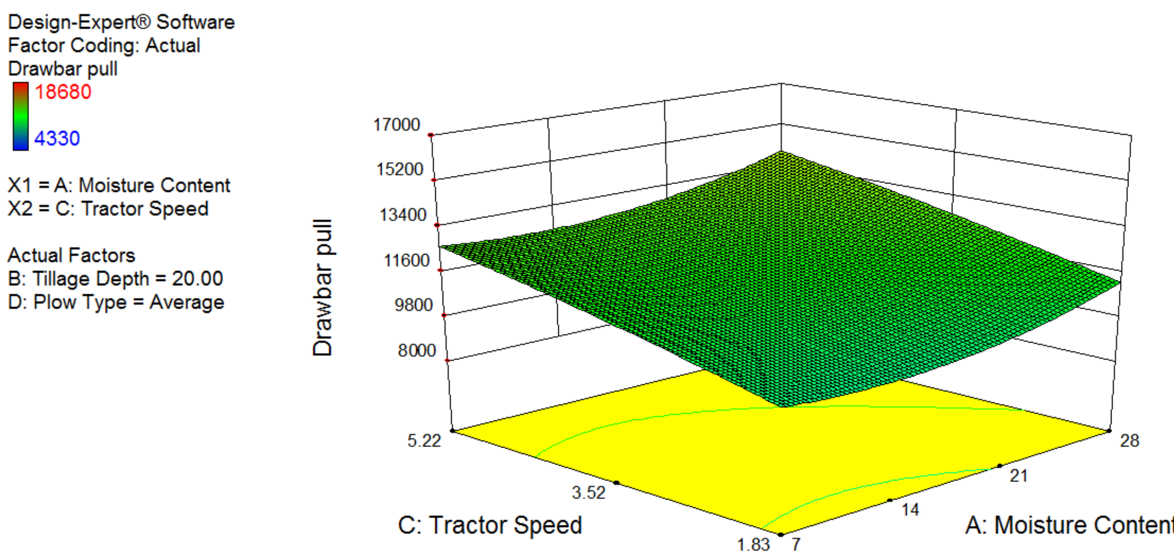

Fig. (2): Effect of soil moisture, forward speed of the tractor and their interaction on the draft force.

Fig. (3) shows the effect of the interaction between the plowing depth and the tractor forward speed on the draft force. It is also noted from Table (3) that there is a remarkable effect of the interaction on the draft force. The draft force increases with the increase in both the plowing depth and the tractor forward speed, where the highest draft force of 15324 N was recorded at a speed of 5.22 km h^{-1} and a plowing depth of 25 cm, and the lowest draft force of 7086 N was recorded at a speed of 1.83 km h^{-1} and a plowing depth of 15 cm. These results were in agreement with those of Ranjbarian *et al*. (2017)

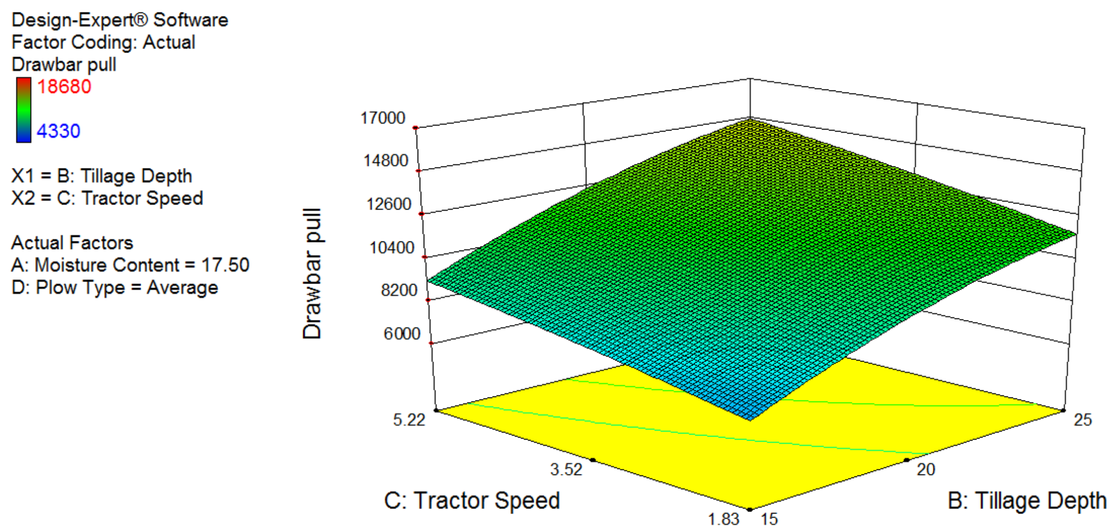

Fig. (3): Effect of soil moisture, the forward speed of the tractor and their interaction on the draft force.

Fig. (4) shows the effect of plow type, soil moisture and their interaction on the draft force. As shown in Table (3) the plow type has a substantial effect on the pulling force. Plowing with a moldboard plow recorded the highest draft force, reaching 12671 N, and the lowest draft force when plowing with a disc plow, reaching 9966 N. Meanwhile, the draft force when plowing with a chisel plow, reached 10840 N. The reason for the variance in the draft force is due to the nature of the work of each plow and its design. The moldboard plow works to cut, lift and turn the soil, which increases the soil's resistance to plowing and thus increases the draft force. However, the rotation of the disc in the disc plow helps to absorb the soil force through the rotation of the disc during plowing, facilitates the movement of the plow in the soil and thus reduces the draft force compared to the moldboard and chisel plows. The chisel plow is a crawler plow that works to break and loosen the soil without turning it over, therefore, the soil resistance during plowing is less than the moldboard plow, which reduces the draft force of the plow. This result is consistent with Ranjparian *et al*., (2017), who noted that the moldboard plow recorded the highest draft force, followed by the chisel plow and then the disc plow. From the results of the statistical analysis table (Table 3), it is noted that there are no serious differences in the effect of the interaction between the type of plow and soil moisture on the draft force.

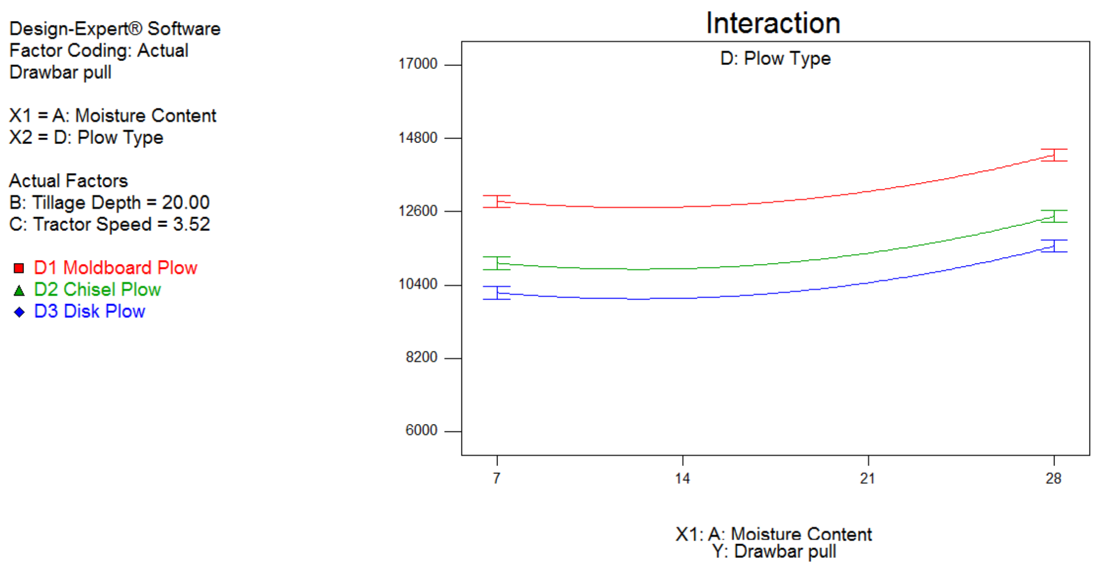

Fig. (4): Effect of soil moisture, plow type and their interaction on the draft force.

Fig. (5) shows the effect of the interaction between the depth of tillage and the type of plow on the draft force, Table (3) shows that the interaction between the depth of tillage and the type of plow was serious, as the highest draft force was recorded at 15009 N when plowing with the moldboard plow at a depth of 25 cm, and the lowest draft force reached 6985 N when plowing with the disk plow at a depth of 15 cm.

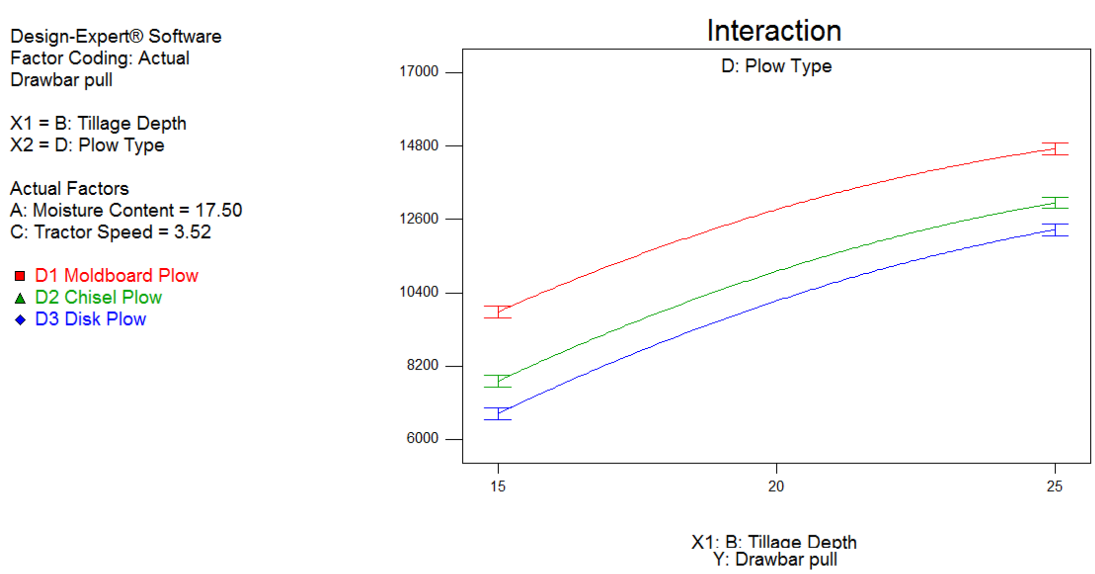

Fig. (5): Effect of tillage depth, plow type and their interaction on the draft force.

Fig. (6) shows the effect of interaction between the type of plow and the forward speed of the tractor on the draft force, Table (3) shows there is a clear effect to the interaction on the draft force. Plowing with the disk plow at a forward speed of 1.83 km h^{-1} was recorded the lowest draft force of 8809 N, while the tillage with the moldboard plow at a forward speed of 5.22 km h^{-1} was recorded the highest draft force of 14411 N.

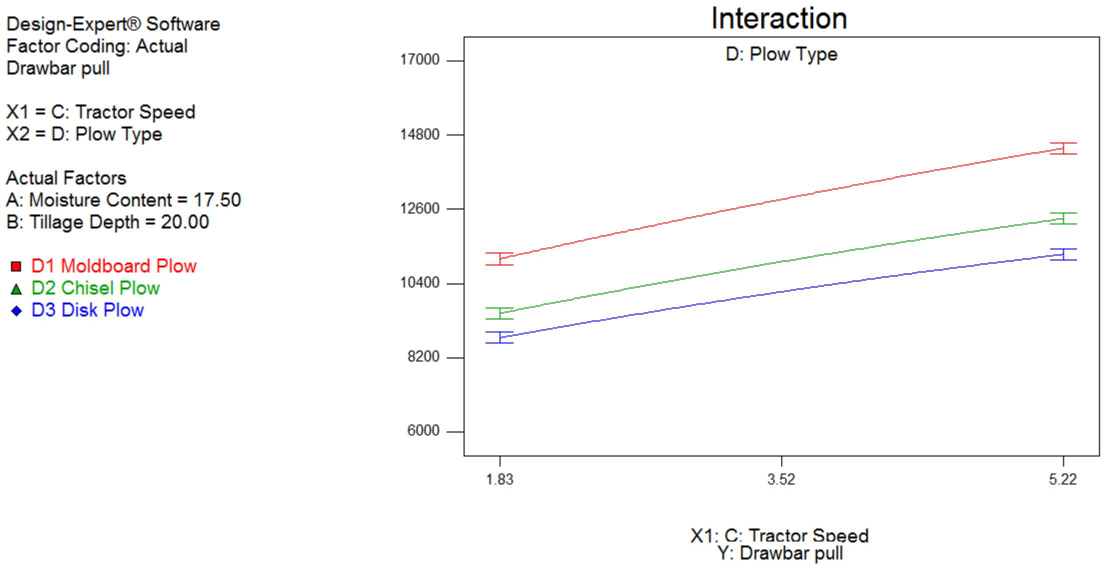

Fig. (6): Effect of the forward speed of the tractor, the type of plow and their interaction on the draft force.

Fig. (7) presents the effect of the study factors on the draft force, it is noted that depth of tillage is considered the most significant factor in measuring the draft force as the force increases with increasing the depth. Meanwhile, the second and third effecting factors are the forward speed, and the soil moisture, respectively. These results are consistent with what Almaliki (2018) found.

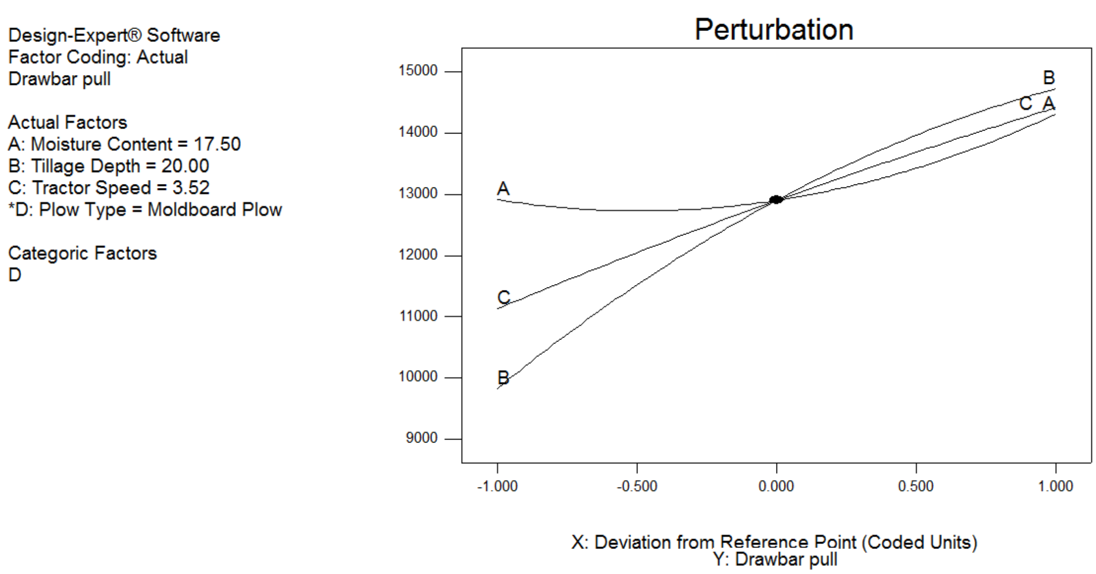

Fig. (7): The relative importance of the study factors (soil moisture, forward speed and plowing depth) on the draft force.

Fig. (8) shows the regression analysis of the draft force under the influence of different study factors. It is noted that the data spread is suitable, as the coefficient of determination

R^2 = 0.9531, which indicates that this model has high robustness and can be applied with high efficiency compared to field data. Table (4) shows the mathematical equations for each type of plow to predict the draft force according to the operational conditions of the plow, where through these equations the draft force of the plow can be predicted by entering the variables of the plowing depth, speed and soil moisture.

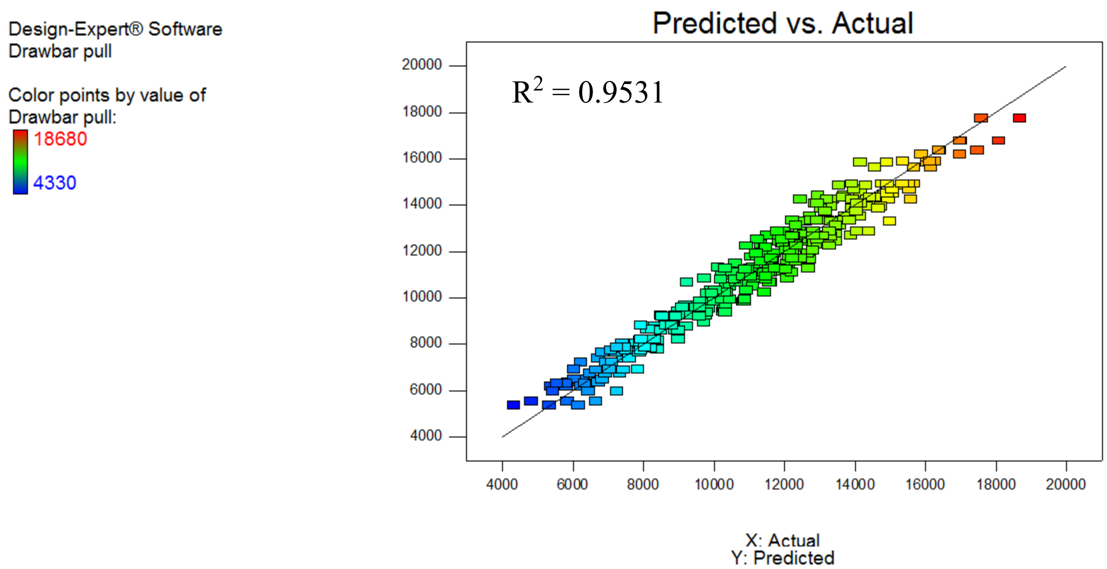

Fig. (8): Relationship between field-measured and predicted draft force.

Table (4): Equations for predicting draft force for different types of plows.

Plow type	Final equation
Moldboard plow	Draft force = –9146.16596 – 158.79997 * M + 1443.05687 * D + 1034.40474 * S + 1.04854E–014 * M * D + 3.62909E–014 * M * S + 12.29217 * D * S + 6.43869 * M^2 – 24.92593 * D^2 – 44.19375 * S^2
Chisel plow	Draft force = –11423.75234 – 158.79997 * M + 1488.94576 * D + 894.66227 * S + 1.04854E–014 * M * D + 3.62909E–014 * M * S + 12.29217 * D * S + 6.43869 * M^2 – 24.92593 * D^2 – 44.19375 * S^2
Disk plow	Draft force = –12296.54020 – 158.79997 * M + 1505.83465 * D + 793.83000 * S + 1.04854E–014 * M * D + 3.62909E–014 * M * S + 12.29217 * D * S + 6.43869 * M^2 – 24.92593 * D^2 – 44.19375 * S^2

Where: M= Moisture Content D= Tillage Depth S= forward speed

Slippage Percentage

Fig. (9) presents the effect of soil moisture and plowing depth on the slip rate. It is noted from Table (5) that soil moisture has a clear effect on the tractor slip rate. The lowest slip rate recorded is 12.39% when the soil moisture is 14%, meanwhile the slip increases by 12.43, 29.78 and 116.63% at soil moisture of 7, 22 and 28% respectively. This can be attributed to the high soil strength due to the increase in the soil molecular cohesion when the soil is dry (7%), which increases the soil's resistance to plowing and thus increases the draft force and slip.

As for increasing the soil moisture to 14%, the soil molecular cohesion decreases due to the presence of water films around the soil particles, which reduces the soil strength and reduces its cohesion and thus reduces the slip. When the soil moisture is high at 22 and 28%, the cohesion of the water films in the soil increases and the cohesion between the soil and the tractor tires decreases due to the presence of water between the soil and the tire and the increased adhesion of the soil to the frame and the plow, which increases the draft force and thus increases the tractor slippage. These findings are consistent with what was reached by Amponsah *et al.*, (2014), who noted an increase in slippage with increasing soil moisture. The results of the analysis of variance in Table (5) also showed that the plowing depth has a considerable effect on the percentage of tractor wheel slippage, where increasing the plowing depth has led to an increase in the slippage, reaching 12.52, 17.10 and 22.32% for depths of 15, 20 and 25 cm, respectively. This result was due to the increase in the load on the tractor and the increase in soil cohesion and apparent density with increasing soil depth, which increases the draft force and increases slippage. This is consistent with the results of Al aridhee *et al.*, (2020). The results of the statistical analysis (Table 5) shows a significant effect of the interaction between soil moisture and plowing depth on the slip rate. The highest value of the slippage percentage was 31.49% at soil moisture of 28% and a plowing depth of 25 cm, meanwhile the lowest slippage percentage was 7.95% at soil moisture of 14% and a plowing depth of 15 cm.

Fig. (10) shows the effect of soil moisture and forward speed of the tractor on the slippage percentage. It is noted from Table (5) that the speed has a remarkable effect on the tractor slippage. The slippage percentage increases while increasing the speed from 1.83 to 3.06 and 5.22 km h^{-1} by 13.45, 17.67 and 20.82%, respectively. The reason for this is due to the increased acceleration of soil masses with increasing speed, which increases the resistance of the soil to plowing and thus increases the slippage. This result is consistent with what Tayel *et al.*, (2015) reached. The results in Table (5) also shows a remarkable effect of soil moisture and forward speed of the tractor on the slippage percentage. The highest slippage percentage was 30.13% at 28% soil moisture, when the forward speed was 5.22 km h^{-1}, meanwhile the lowest slippage percentage was 8.89% at 14% soil moisture at a forward speed of 1.83 km h^{-1}.

Table (5): ANOVA Table Indicating the Effect of Study Factors on Slippage.

Source	Sum of Squares	df	F- Value	p-value Prob > F
Model	281.43	14	328.27	**< 0.0001**
A-Moisture Content	98.22	1	1947.66	**< 0.0001**
B-Tillage Depth	79.05	1	1567.55	**< 0.0001**
C-Tractor Speed	41.04	1	813.89	**< 0.0001**
D-Plow Type	6.90	2	68.37	**< 0.0001**
AB	1.77	1	35.05	**< 0.0001**
AC	0.84	1	16.62	**< 0.0001**
AD	0.054	2	0.53	**0.5887**
BC	4.83	1	95.68	**< 0.0001**
BD	0.55	2	5.46	**0.0047**
CD	0.86	2	8.54	**0.0002**

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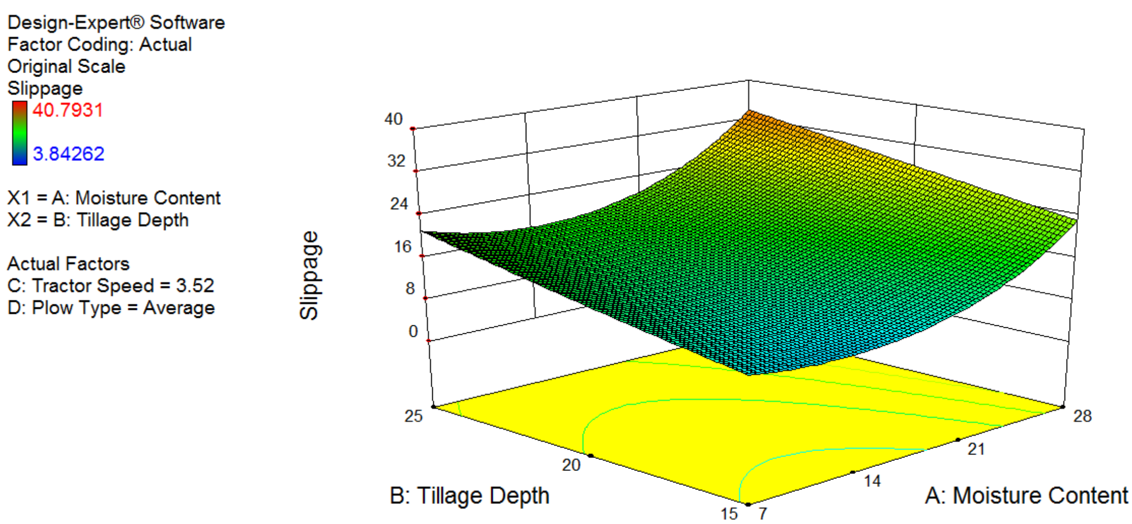

Fig. (9): Effect of soil moisture, tillage depth and their interaction on the slippage percentage.

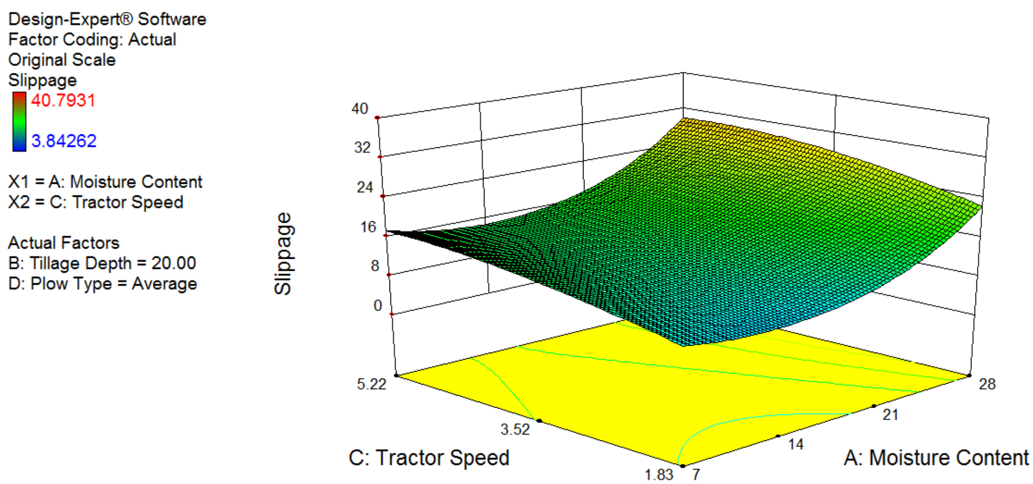

Fig. (10): Effect of soil moisture, the forward speed of the tractor and their interaction on the slippage percentage.

Fig. (11) shows the effect of the interaction between the plowing depth and the tractor forward speed in the slippage percentage. The analysis of variance in Table (5) show that the interaction effect is crucial on the slippage percentage. The slippage increases with increasing plowing depth and tractor forward speed as a result of the increase in soil strength when depth increases. The acceleration of soil masses also increased with increasing speed, which increases the soil resistance to plowing and thus increases the slippage percentage. The highest slippage percentage achieved was 28.11% at a depth of 25 cm and a speed of 5.22 km h^{-1}, on the other hand, the lowest slip rate was 10.66% at a depth of 15 cm, and a speed of 1.83 km h^{-1}. This result is consistent with what Tayel *et al*., (2015) reached.

Fig. (12) shows the effect of plow type, soil moisture and their interaction on the slippage percentage. It is noted that the plow type has a notable effect on the slippage percentage (Table 5). The disc plow outperforms the other types of plows where it recorded the lowest slippage percentage of 15.89%, while the moldboard plow and chisel plow recorded a slippage percentage of 19.02 and 17.02%, respectively. This is due to the nature of the disc plow and its design, as it contains rotating discs that rotate when there is any resistance in the soil, as well as the presence of scrapers that clean the discs from the soil stuck to the discs, which reduces the effort on the plow and thus reduces the slippage rate. the moldboard plow works to split, lift and turn the soil, which increases the soil's resistance to the plow and thus increases the slippage. In addition, the chisel plow works to split and loosen the soil without turning it, which reduces the soil's resistance to the plow compared to the moldboard plow. From the variance analysis in table (Table 5), it is clear that there is no significant effect for the interaction between the type of plow and soil moisture on the slippage percentage.

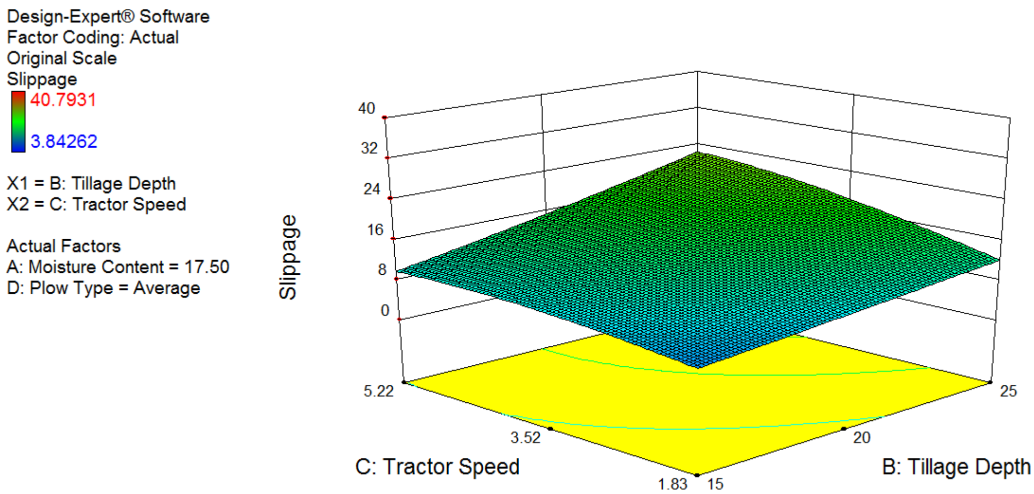

Fig. (11): Effect of tillage depth, forward speed of tractor and their interaction on the slippage percentage.

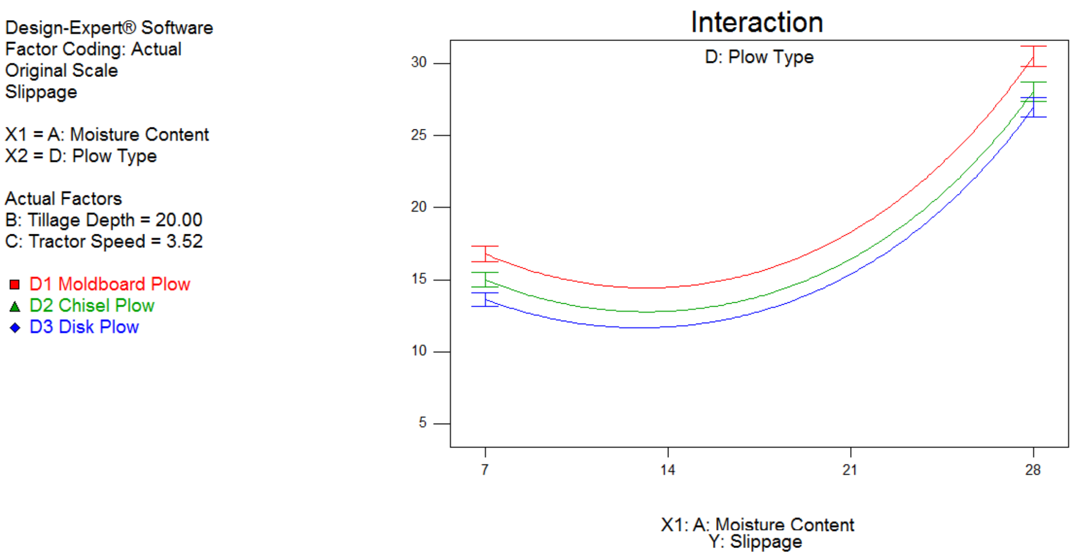

Fig. (12): Effect of soil moisture and plow type and their interaction on the slippage percentage.

Fig. (13) shows the effect of plowing depth and plow type and their interaction on the slippage percentage. The results illustrate that the interaction between plowing depth and plow type is significant as shown in (Table 5). Plowing with a moldboard plow at a depth of 25 cm recorded the highest slippage percentage of 24.65%, meanwhile the lowest recorded slippage percentage was 11.73% when plowing with a disc plow at a depth of 15 cm.

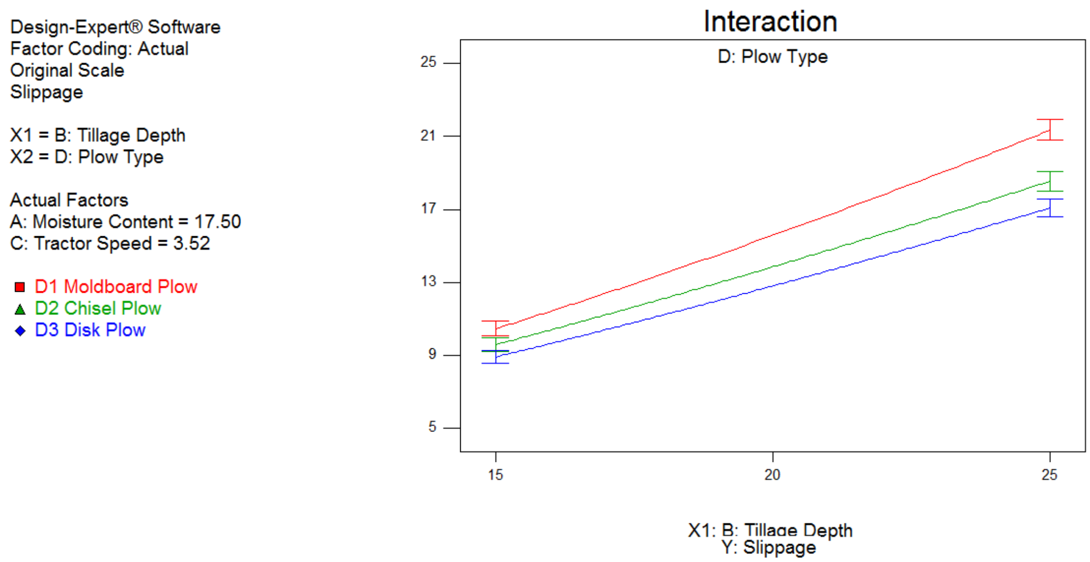

Fig. (13): Effect of tillage depth, plow type and their interaction on the slippage percentage.

Fig. (14) shows the effect of the interaction between the type of plow and the forward speed of the tractor on the slippage percentage. Table (5) shows that there is a significant effect of the interaction on the slippage percentage, the moldboard plow with high forward speed of 5.22 km h^{-1} recorded the highest slippage percentage of 23.37%, while plowing with the disc plow at a forward speed of 1.83 km h^{-1} recorded the lowest slippage percentage of 12.75%.

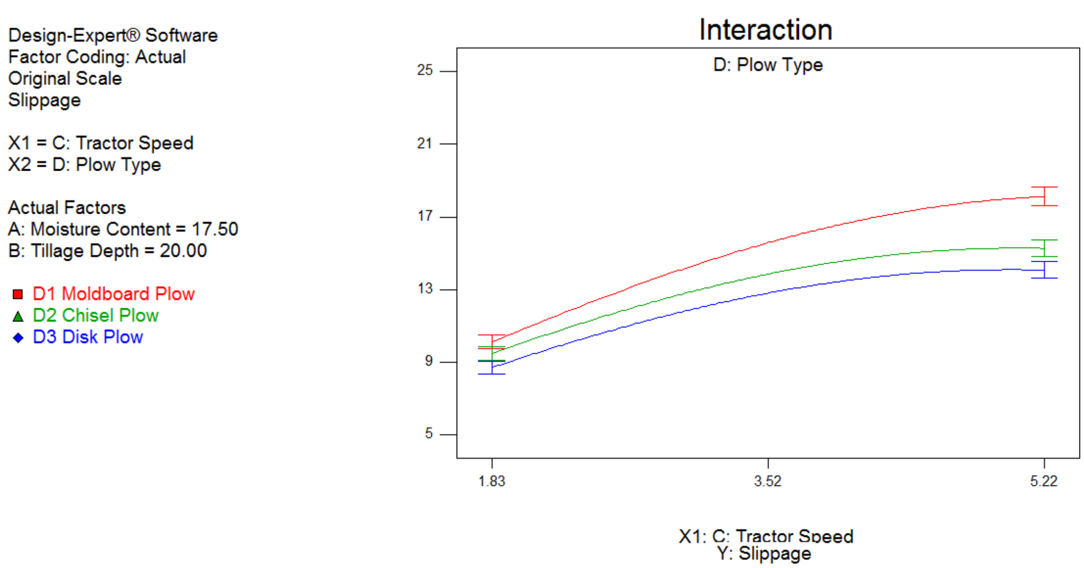

Fig. (14): Effect of the forward speed of the tractor, the type of plow and their interaction on the slippage percentage.

Fig. (15) shows the effect of the study factors on the slippage percentage. The results show that the factor that affects the most on the slippage percentage is soil moisture, followed by plowing depth, then the forward speed. This indicates that soil moisture is an important factor in measuring the tractor slippage percentage, as the slippage percentage is affected by changes in soil moisture, followed by depth factor and then the speed.

Fig. (16) shows the regression analysis data for the slippage percentage under the influence of different study factors. The data spread around the regression line is good. with coefficient of determination R^2 = 0.9480, which indicates that this model has high robustness and can be applied with high efficiency compared to field data. Table (6) shows the mathematical equations for each type of plows to predict the slippage percentage according to the different operating conditions of the plow. Through these equations, the plow slippage percentage can be predicted by entering variables such as plowing depth, speed, and soil moisture.

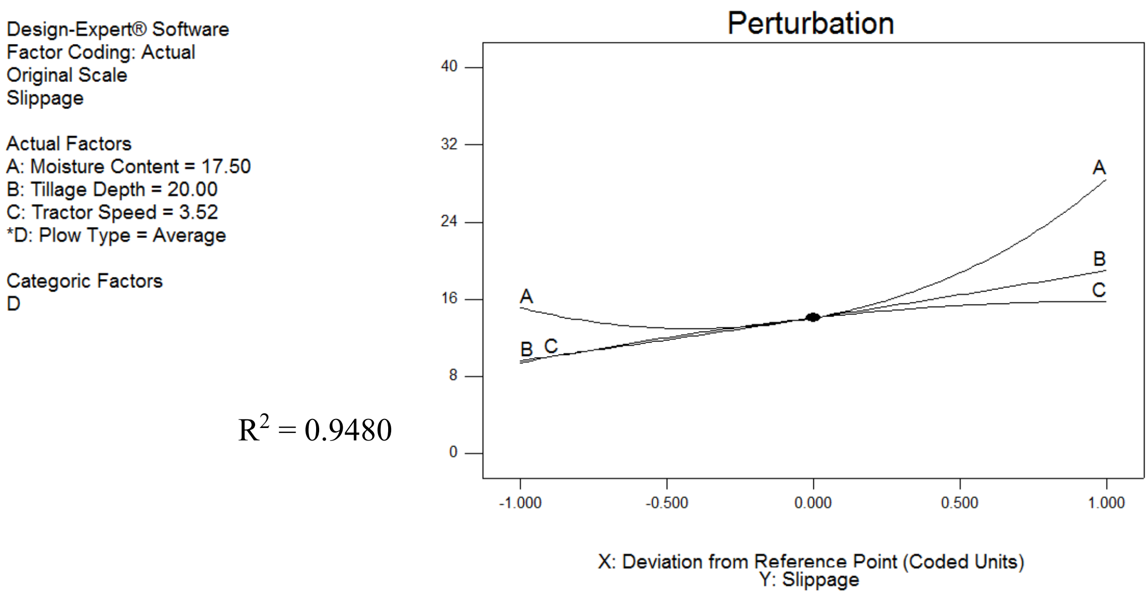

Fig. (15): Relative importance of study factors (soil moisture, forward speed and tillage depth) on the slippage percentage.

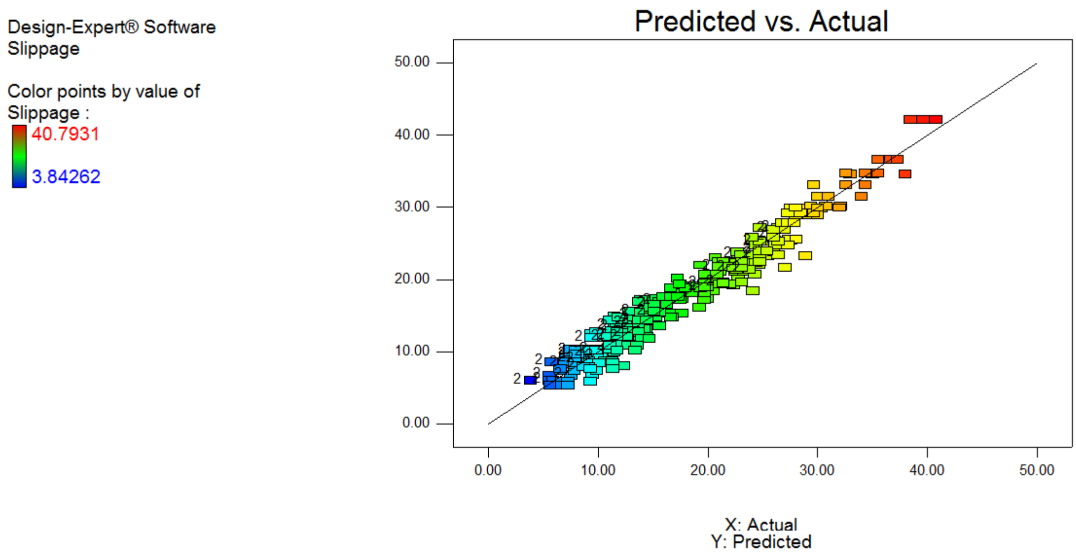

Fig. (16): Relationship between calculated and predicted slippage percentages.

Table (6): Equations for predicting slippage percentages for different types of Plows.

Plow Type	Final Equation
Moldboard Plow	Sqrt(Slippage) = + 0.37905 – 0.14496 * M + 0.13579 * D + 0.53164 * S – 2.27608E–003 * M * D – 4.56678E–003 * M * S + 0.021333 * D * S + 7.84073E–003 * M^2 – 8.12174E–004 * D^2 – 0.079475 * S^2
Chisel Plow	Sqrt(Slippage) = + 0.76250 – 0.14489 * M + 0.11825 * D + 0.45810 * S – 2.27608E–003 * M * D – 4.56678E–003 * M * S + 0.021333 * D * S + 7.84073E–003 * M^2 – 8.12174E–004 * D^2 – 0.079475 * S^2
Disk Plow	Sqrt(Slippage) = + 0.71607 – 0.14150 * M + 0.11192 * D + 0.44971 * S – 2.27608E–003 * M * D – 4.56678E–003 * M * S + 0.021333 * D * S +7.84073E–003 * M^2 – 8.12174E-004 * D^2 – 0.079475 * S^2

Where: M= Moisture Content D= Tillage Depth S= forward speed

Conclusion

This work aims to predict the traction requirements represented by draft force and slippage percentage using three machines (moldboard plow, disc plow and chisel plow) under the influence of different speeds, depths and soil moisture levels.

The design expert software was used for the prediction process and predictive equations were developed according to the different study factors. The effect of plowing depth, speed, moisture and plow type significantly effects draft force and the slippage percentage.

The draft force increased by 62.84 and 29.05% with increased the depth from 15 to 25 cm and the speed from 1.83 to 5.22 km h^{-1}, respectively.

The slippage percentage increased by 78.27 and 54.79% with an increase in the depth from 15 to 25 cm and the speed from 1.83 to 5.22 km h^{-1}, respectively.

The soil moisture of 14% gave the best results for the draft force and slippage percentage, reaching 10335 N and 12.39%, respectively.

The disc plow was superior in terms of the lowest draft force and slippage compared to the moldboard plow and chisel plow, with draft force of 9966 N and slippage of 15.90% for the disc plow.

The predicted data gave equations that can be used efficiently to obtain the draft force and the slippage under different operating conditions with a coefficient of determination (R^2) of 0.9531 and 0.9480 for draft force and slippage respectively compared to field data.

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Contributions of authors

M.F. A: Collection of specimens, Laboratory techniques, wrote and revised the manuscript.

S.A.A: Suggestion the proposal of the article, wrote and revised the manuscript.

S.M.A: Suggestion the proposal of the article, revised the manuscript.

Conflicts of interest

The authors declare that they have no conflict of interests.

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Ethical approval

All conditions related to human safety and health were followed in this research.

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التنبؤ بمتطلبات السحب ونسبة الانزلاق لثلاثة أنواع من المحاريث في ظروف تشغيليه مختلفة

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المستخلص: هدفت الدراسة إلى التنبؤ بمتطلبات الجر التي تمثلها قوة السحب ونسبة الانزلاق تحت مستويات مختلفة من رطوبة التربة (7 و14 و22 و28٪) واستخدام ثلاثة محاريث: محراث مطرحي قلاب ومحراث حفار ومحراث قرصي بثلاثة أعماق حراثة (15 و20 و25 سم) وثلاثة سرع امامية (1.83و3.06 و5.22 كم ساعة$^{-1}$) في تربة مزيجة طينية في القرنة، البصرة. تم تحليل البيانات باستخدام برنامج Design Expert لنمذجة قوة السحب والانزلاق وأداء الجرار. بناء على النتائج التي تم الحصول عليها، وجد أن قوة السحب زادت بزيادة العمق من 15 إلى 25 سم والسرعة من 1.83 إلى 5.22 كم ساعة$^{-1}$ بنسبة 62.84٪ و29.05٪ على التوالي، وازداد الانزلاق بزيادة العمق من 15 إلى 25 سم والسرعة من 1.83 إلى 5.22 كم ساعة$^{-1}$ بنسبة 78.27 و54.79٪ على التوالي. كما أعطت رطوبة التربة 14٪ أقل قوة سحب وانزلاق حيث بلغت 10334 نيوتن و12.39٪ على التوالي مقارنة بمستويات الرطوبة الأخرى. كما أظهرت النتائج أن استخدام المحراث القرصي سجل أقل قوة سحب وانزلاق بلغ 9966 نيوتن و15.90٪ على التوالي، بينما أدى استخدام المحراث المطرحي إلى زيادة قوة السحب والانزلاق حيث بلغت 12671 نيوتن و19.02٪ على التوالي. أظهر تحليل البيانات أن النموذج المطور يتمتع بقدرة جيدة على التنبؤ مقارنة بالبيانات الحقلية، حيث كان معامل التحديد لقوة السحب والانزلاق (R^2) 0.9531 و0.9480 على التوالي.

الكلمات المفتاحية: قوة السحب، السرعة الأمامية، عمق الحراثة، التنبؤ، الانزلاق، محتوى رطوبة التربة.