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Effect of the Operating Depth and the Lateral Inclination Angle on the Draft Force Requirements and the Lateral Force of the Vertical and Laterally Inclined Mole Plows in Silt Clay Soil

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***Abstract*: A lateral inclined mole plow was designed for making moles underneath the soil surface to drain the excess water from the soil top layers and to reduce the risk of the soil salinity. The new mole plow was designed as alternative to CVMP. CVMP suffers from many drawbacks among them the low field performance, low mole durability and quick blockade by the soil particles. LIMP has many advantages and optimum to CVMP in many field performance parameters. The main advantage is, its leg can be laterally moved to offset the position of the mole from the disturbed soil and that reduces the risk of early blockade as the case with CVMP.**

LIMP was tested in silt clay soil using five operating depths (30, 35, 40, 45 and 50cm), five lateral inclination angles (0. 15, 25, 35 and 45^0) and two moisture content levels 26.12 and 35.38%. The field performance of LIMP was contrasted with that of CVMP to determine the optimum field performance of either of them. In part 1, the draft force requirements of both types of plows and the lateral force acting on LIMP were analyzed to evaluate their field performance. The draft force requirement of CVMP and LIMP increased with operating depth. The draft force requirement of LIMP was higher than that for CVMP for all operating depth and for both moisture content levels. The lateral force of LIMP increased with operating depths and in both moisture content levels. The highest draft force requirement (28.31kN) and lateral force (10.56kN) for LIMP were recorded for the deepest operating depth (50cm), the greatest lateral inclination angle (45^0) in the higher soil moisture content level (35.38%). Whereas, the lowest draft force requirement (12.33kN) and lateral force (3.40kN) were recorded for the shallow operating depth (30cm) and smallest lateral inclination angle (15^0) in the lower soil moisture content level of (26.12%). From the field observations LIMP was more stable in soil (moving in straight line) as the operating depth increased and with higher moisture content levels tested despite of the high lateral force with deeper operating depth. The best mole was obtained at deepest operating depth, lateral angle of 35^0 and the highest moisture content (35.38%) where the soil more plastic.

Keywords: Conventional mole plow; lateral inclined mole plow; lateral inclination angle; draft force requirement; lateral force Abbreviation: CVMP= Conventional Mole Plow; LIMP= Lateral Inclined Mole Plow; M.C. = Moisture Content

1.0 INTRODUCTION

The soils of southern of Iraq are generally ranged between loamy silt clay to silt clay. These soils are classified as heavy soils. They suffer from many problems among them high bulk density, low total porosity, compacted layers, hard pans and high water table, close to the soil surface (Aday et al, 2016a; Aday et al, 2016b). These problems reduce the soil infiltration considerably which negatively affect the soil microorganism activity and increase the soil salinity. The high salinity exists at the top layers where the plant roots grow and that was because the high water table and high water evaporation due to the soil capillary activity (Abdulkareem et al, 2018; Aday and Al-muthafar, 2018). The compacted layers and the hard pans are widely existing in the heavy soils which both play big role in soil salinity and plant roots impeding because they reducing the drainage of the excess water (Aday et al, 1993; Aday, 2005). To eliminate or at least reduce the effect of these problems the soil physical properties should be improved such as reducing the soil bulk density and increasing the soil total porosity. These two soil physical parameters can be achieved by disturbing the soil compacted layers and shattering the hard pans (Godwin et al, 1981; Mckyes and Maswaure, 1997). The soil disturbance increases the soil pore sizes and the total soil porosity which improves the soil water infiltration and hence reducing soil salinity, encouraging the soil microorganism activity and eliminating the roots impeding (Mckyes and Desir, 1984, Aday, 2011).

The convenient plow for such conditions is the mole plow. It can disturb the top soil layers, shatter the compacted layers and the hard pans at depth moreover, it can form moles to drain the soil excess water from the plant roots zone (Godwin et al, 1981). There are two types of mole plows namely, vertical and laterally inclined mole plows. CVMP suffers from many problems among them the mole exists directly underneath the disturbed soil. Thus when the disturbed soil was irrigated the small soil particles washed down and accumulated inside the mole causing mole blockade. Moreover, the soil confine pressure in most cases is not enough on the foot of CVMP to form regular and good mole because most of the soil above the foot disturbed by the leg. In additional to that the specific resistance of CVMP is high whereas, its disturbed area and the energy utilization efficiency are low. These problems lead to design LIMP (Aday, 2012).

In this research CVMP and LIMP were tested in the field to evaluate their field performance to determine the optimum field performance of either of them. The evaluation parameters used were the draft force requirement, the lateral force, disturbed area, specific resistance and the energy utilization efficiency. In part (1) the draft force requirements of LIMP and CVMP and the lateral force acting on LIMP were analyzed and compared for both plows. The remaining parameters were analyzed in parts 2 and 3. Both plows were tested in silt clay soil using four lateral inclination angles (0, 15, 25, 35 and 45^0) (angle 0^0 for CVMP), five operating depth (30, 35, 40, 45 and 50cm). The experiments were conducted in two soil moisture contents levels 26.12 and 35.38%.

2.0 MATERIALS AND METHODS

2.1 The lateral inclined Mole plow

The lateral inclined mole plow (LIMP) consists of a frame of high strength to withstand the stresses impose on the plow by the soil, Fig. 1. The frame was provided with three attachment points to link the plow to the tractor. The plow was provided with two different diameter cylinders. The smaller diameter cylinder was fitted inside the cylinder of big diameter. A small clearance was left between them to let the inner cylinder move freely inside the outer cylinder. The outer cylinder was fastened tightly to the frame while the inner cylinder was left free to rotate inside the outer cylinder. Two slots were made on both cylinders for the leg of the plow to pass through them. The leg was fastened tightly on the inner cylinder. This mechanism let the leg of the plow move freely sideways. The leg was provided with foot and it was fixed at forward angle (rake angle) of 70^0. The penetration angle (the attack angle) of the foot was 30^0. An expander was attached to the rear of the foot. The plow was provided with two supporter bars, Fig. 2. The left side supporter bar was to absorb the soil side force acting on the laterally inclined leg whereas, the right side supporter bar is to change the lateral angle of the leg and also to absorb part of the lateral force imposed on the leg from the soil. The plow was also provided with longitudinal supporter bar link the leg with frame. The function of this supporter was to absorb the soil resistance force imposed by the soil on the front of the leg.

2.2 The soil physical and mechanical properties

The soil moisture content and the soil bulk density were measured using the methods described in Black et al (1983). The lower and upper plastic limits were measured using the methods described in Head (1980). The soil cohesion and soil internal friction angle were measured using the Annulus ring which was described in Smith (1978). The soil penetration angle was measured using hydraulic penetrometer as mentioned in Gill and Vader (1968).

2.3 Draft force requirement measurement

The draft force requirement of CVMP and LIMP were measured by hydraulic dynamometer for five operating depths (30, 35, 40, 45 and 50cm), five laterally inclination angles (0, 15, 25, 35 and 45^0) and two moisture content levels (26.12%) and (35.38%). The experiments were conducted in silt clay soil.

The experiments were carried out by attaching CVMP and then LIMP to a tractor consecutively. A hydraulic dynamometer was used to measure the draft force requirement of CVMP and LIMP. The hydraulic dynamometer was attached to the towing tractor-CVMP combination by one end and to a flexible cable from the other end. The second end of the flexible cable was attached to the tractor-CVMP combinations. The same operation repeated for the tractor-LIMP combination.

The operating depth of CVMP and the operating depth of LIMP and the laterally inclination angle of LIMP were predetermined. The gear box of the towed tractor was left neutral. The engine of the towing tractor was fixed on 1500rpm and then put in gear and left to move 3m to approach the maximum forward speed. The measurements were taken for a distance of 15m. Each run was repeated three times. The experiments were carried out for all operating depths and lateral inclination angles in both moisture content levels. The draft force was calculated by Eq. (1).

F_t=0.8+0. 44165P ………….(1)

Where: F_t= the draft force of the tractor-plow combination (kN)

P= the readings of the hydraulic dynamometer (bar)

The rolling resistance of the towed tractor was measured in the field by pulling the tractor-plow combination and the plow was out of the soil. The rolling resistance was calculated using Eq. (1).

The draft force of the plow was calculated using Eq. (2).

F=F_t-R …………….(2)

Where: F= the plow draft force (kN)

R= the rolling resistance (kN)

2.4 Side force measurement

LIMP pushes the soil sideways and the soil reacts accordingly and imposes a lateral force on the LIMP leg. The lateral force creates friction force on the leg which increases the draft force requirement. Thus it was necessary to measure the lateral force as well as to determine the changes occurred in its values with lateral inclination angles and soil moisture contents. The lateral force was measured using especial hydraulic dynamometer, Fig. 3. The hydraulic dynamometer was attached from one end to the tractor drawbar pull which was fastened firmly to the tractor chassis, whereas, the other end was attached to the lower link of the tractor hydraulic system which the plow attached to. Both ends of the hydraulic dynamometer were attached to multiple holes' channel bar to change the positions of the dynamometer according to the plow depth. The dynamometer was provided with gauge to measure the lateral force. The lateral force was calculated by taking moment about the end of the lower link of the hydraulic system of the tractor by using Eq. (3) and Figs. 2b and 3.

$$F_S = \frac{P \cdot A \cdot L_1}{L_2 \cdot \cos\theta} \qquad \text{..............(3)}$$

Where: F_S= the lateral force acting on the mole plow leg (kN)
P= readings recorded from the dynamometer ($kN.m^{-2}$).
A= the internal area of hydraulic cylinder (m^2)
L_2 = the distance between the hydraulic dynamometer and the attached point of the lower link of the hydraulic system to the tractor (B) (m), Fig. 3.
L_1= the vertical distance between the lateral force (F_S) (A) (Fig 2b) and the horizontal line passing through point (B) (m).
ϴ = the lateral inclination angle of the plow leg (degree).

The statistical analysis of the results of the draft force requirement and the lateral force is shown in table (2).

3.0 RESULTS AND DISCUSSION

3.1 Effect of the operating depth and the soil moisture content levels on the draft force requirement of CVMP and LIMP and the lateral force of LIMP

The draft force requirements of CVMP and LIMP significantly (P<0.01), table 2, increased with operating depth, Fig. 4. This was related to the greater volume of soil manipulated by both plows, which required extra force to be moved because of its high resistance for movement. Moreover, the soil cohesion and adhesion increased considerably with operating which both required great force to be overcome. Comparing the draft force requirement of CVMP and that of LIMP, CVMP required less draft force for all operating depth tested and that was because CVMP manipulated less volume of soil than LIMP as well as CVMP did not experience a lateral force so that it did not suffer from the friction force which created by the lateral force as the case with LIMP.

The draft force requirements of CVMP and LIMP also increased with the soil M.C. and that was due to the soil cohesion and adhesion which both of them were higher in the soil of higher M.C. (table 1). However, the draft force requirement of CVMP was lower than that for LIMP for both M.C. levels. This was because CVMP did not exposed to the lateral force so that no soil adhered to its leg which enabled the soil to move freely and that contrary to LIMP where the lateral force adhered (smeared) the soil to its leg especially in the soil of M.C of 35.38%. The adhered soil put greater resistance on the soil movement on the leg and therefore resulted in higher resistance and draft force.

Comparing the effect of the operating depth and the soil M.C. on the draft force requirement of both plows, the operating depth was more effective on the draft force than the soil M.C. For example, increasing the operating depth from 30 to 50cm, the draft force of LIMP increased by 62 and 88% and for CVMP by 75 and 75% for M.C. levels of 26.12 and 35.38% respectively. However, increasing M.C. from 26.12 to 45,38%, the draft force of LIMP increased by 29 and 12% and for CVMP by 32 and 32% for the operating depths of 30 and 50cm. This means the effect of the big soil volume which was produced by deeper operating depths required more draft force to be disturbed and moved than overcoming the soil cohesion and adhesion which both increased with the soil moisture content.

For the lateral force, it increased with operating depth and M.C., Fig. 5. This was related to the increase in the volume of soil displaced sideways by LIMP with operating depth which required greater force to be pushed sideways. Moreover, the soil put more resistance on the soil sideways movement as the soil M.C. increased because its cohesion and adhesion increased with operating depth and M.C. The lateral force was higher in the soil of higher M.C. 35.38% comparing with the lower soil M.C. 26.12% and that was related to the higher soil cohesion and adhesion.

The operating depth also surpassed the soil M.C. in its effect on the lateral force. For example, the lateral force increased by 64.6 and 59.5% when the operating depth increased from 30 to 50cm for soil M.C. of 26.12 and 35.38% respectively. Whereas, the lateral force increased by 30.55 and 27.15% when the soil M.C. increased from 26.12 to 35.38% for operating depths of 30 and 50cm respectively.

3.2 Effect of the lateral inclination angle on the draft force requirement and the lateral force of LIMP.

The lateral inclination angle significantly (P<0.01), table 2, increased the draft force requirement of LIMP and that was because as the lateral inclination angle increased the leg of LIMP pushed greater volume of disturbed soil sideways and displaced it further distance away from the movement path of the plow, Fig. 6. The lateral displacement of the greater volume of the soil increased the soil lateral force on the leg which on the other hand increased the friction force on the leg which resulted higher draft force requirement. In additional to that the lateral force increased the smeared soil on the leg especially with higher soil M.C. (35.38%). The smeared soil resisted the soil movement on the leg which leads to higher draft force.

Comparing the draft force requirement of CVMP with that of LIMP, the draft force of LIMP was higher than that for CVMP for all the lateral inclination angles and the difference between them increased as the inclination angle increased. For example, the draft force requirements for LIMP were higher by (average for both moisture content levels) 4, 18, 27 and 39.8% for the lateral inclination angles 15, 25, 35 and 45^0 respectively.

The draft force requirements of LIMP were higher in the soil of higher M.C. (35.38%) comparing with that of the lower M.C. (26.12%). This was related to the higher soil cohesion which resisted the lateral displacement of the soil by LIMP which required extra force to be overcome and that resulted in higher lateral force and then friction force on the leg. The soil adhesion also increased as the soil M.C. increased which required also extra force to be overcome, table (1).

Comparing the effect of the lateral inclination angles and the moisture content on the draft force requirements of LIMP, the lateral inclination angle increased the draft force requirement more than the soil M.C. levels. For example, for lateral inclination angles of (15^0) and (45^0), the draft force requirements of LIMP were higher in the soil of M.C. level of 35.38% by 11.7 and 7.4% comparing with that of M.C. level of 26.12% respectively. Whereas, the draft force requirements increased by 39.7 and 34% when the lateral inclination angles increased from 15 to 45^0 for M.C. levels of 26.12 and 35.38% respectively.

The lateral force increased significantly ($P<0.01$) as the lateral inclination angles increased in both soil M.C. levels, but it was higher in the soil M.C. level of 35.38% than M.C. level of 26.12%, Fig. 7. This was because as the lateral inclination angle increased as the volume of the disturbed soil increased and that but greater resistance on LIMP leg. The supervision of the higher M.C. level on the lower M.C. level in giving higher lateral force was due to the higher moisture content which resisted soil failure and the high soil adhesion which required more power to be cleaned of the LIMP leg and foot.

The highest lateral force value of (10.53kN) was recorded for the lateral inclination angle of 45^0 and M.C. level of 35.38% Whereas, the lowest value (4.91kN) was recorded for lateral inclination angle of 15^0 and M.C. level of 26.12%.

3.3 The interaction effect of the operating depth and the lateral inclination angle on the draft force requirement of CVMP and LIMP

The draft force requirements of CVMP and LIMP increased significantly ($P<0.01$) with both the operating depth and the lateral inclination angle but the average of increase in the draft force was higher with operating depth comparing with lateral inclination angle, Fig. 8. For example, increasing the lateral inclination angle from 15 to 45^0 the draft force requirement increased by 54.8 and 33.1% for operating depth of 30 and 50cm respectively, whereas, increasing the operating depth from 30 to 50cm the draft force requirement increased by 63.6 and 40.6% for the lateral inclination angle of 15 and 45^0 respectively. The draft force requirements of LIMP were higher than that for CVMP and that was because the CVMP disturbed less volume of soil and did not experience a lateral force.

Both parameters significantly ($p<0.01$) increased the lateral force acting on the LIMP, Fig. 9. The greatest value of the lateral force (28.31kN) was recorded for the deepest operating depth (50cm) and largest lateral inclination angle of (45^0). However, the lowest lateral force (13.0kN) was recorded for shallow operating depth (30cm) and smallest lateral inclination angle (15^0). However, the operating depth increased the lateral force by greater amount than the lateral inclination angle. For example, the lateral force increased by 112.5 and 40.8% when the operating depth increased from 30 to 50cm for inclination angle of 15 and 45^0 respectively, but increasing the lateral inclination angle from 15 to 45^0 the lateral force increased by 96.3 and 30% for operating depths of 30 and 50cm respectively. The results showed clearly that the effect of the operating depth on the lateral force decreased as the lateral inclination angle increased.

CONCLUSIONS

1. The draft force requirements of LIMP increased with operating depth, the lateral inclination angles and the soil moisture content. LIMP draft force requirements were higher than that of CVMP for all the operating depths tested.
2. The lateral force acting on LIMP increased with operating depth and the lateral inclination angles for moisture content levels, 26.12 and 35.38%.
3. The highest draft force requirements and lateral force for LIMP were recorded for the deepest operating depth (50cm), the greatest lateral inclination angle of the leg (45^0) in the higher moisture content level (35.38%). The highest values (average) of the draft force requirements and lateral forces were (28.31kN) and (10.56kN) respectively. The lowest draft force requirement and lateral force were recorded for the shallow operating depth (30cm) and smallest lateral inclination angle (15^0) in the moisture content level of (26.12%). The values are (12.33kN) and (3.4kN) respectively.
4. From the field observations LIMP was more stable in soil (moving in straight line) as the operating depth increased and with higher moisture content tested despite of the high lateral force with deeper operating depth.
5.

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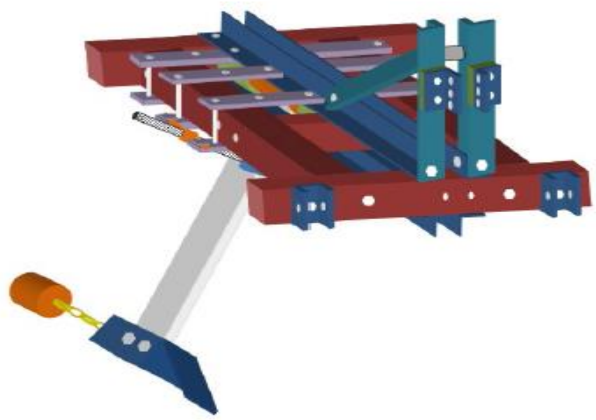
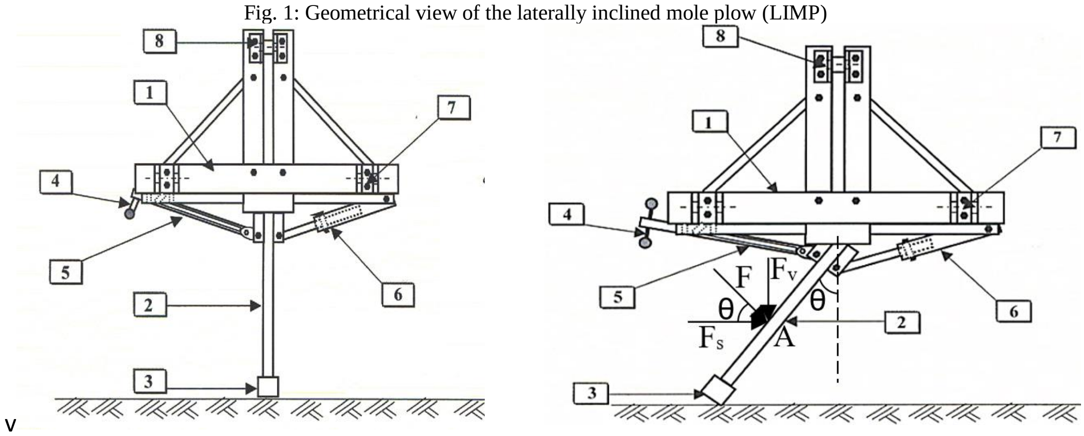
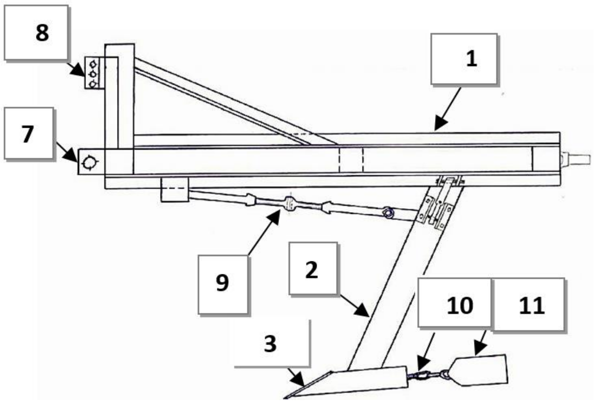


Fig. 1: Geometrical view of the laterally inclined mole plow (LIMP)



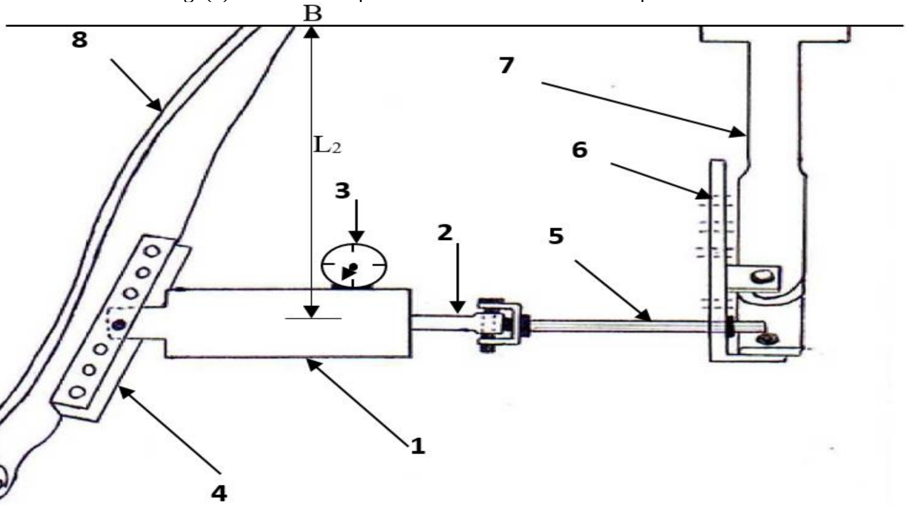
(a) (b)



(c)

1. Frame 2. Leg 3. Foot 4. Handle to operate angle changing mechansim 5. Lateral angle changing mechansim 6. right side supporter 7. Lower attachment point 8. Upper attachment point 9. Longitudinal supporter 10. chain 11. Expander

Fig. (2): The different parts of the lateral inclined mole plow



1. Hydraulic cylinder 2. Piston arm 3. Measuring gauage 4. Multi-hole channel type plate 5. Shaft to connect the drawbar pull and the piston arm 6. plate to change the poistion of shaft (5) 7. Tractor drawbar pull 8. Lower tractor hydraulic system arm.

Fig. 3: Hydraulic dynomometer for the lateral force measurement

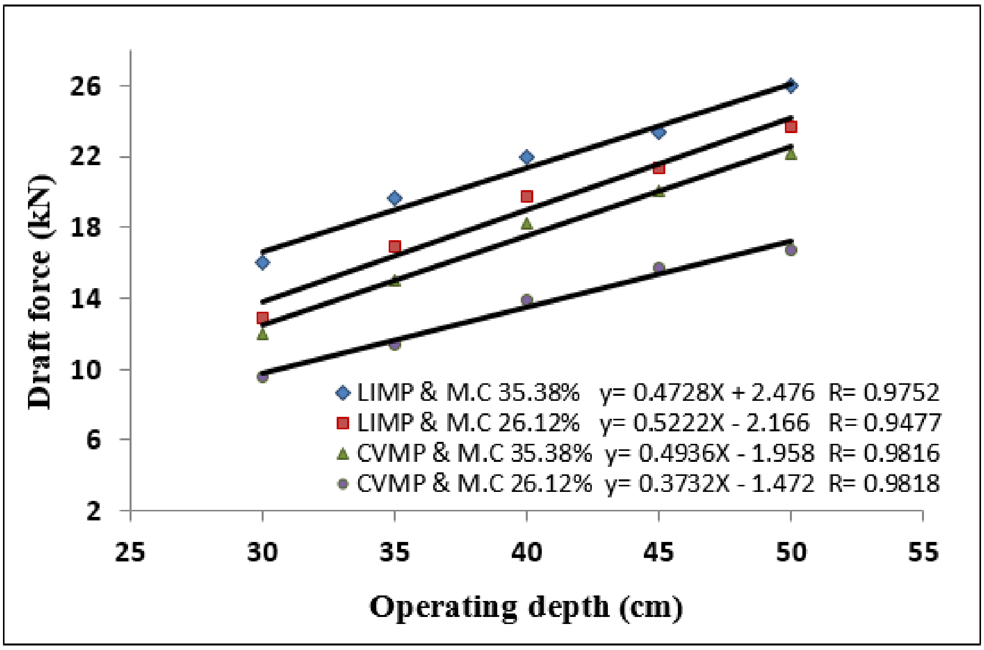


Fig. 4: The draft force versus the operating depth for CVMP and LIMP for two soil Moisture content levels

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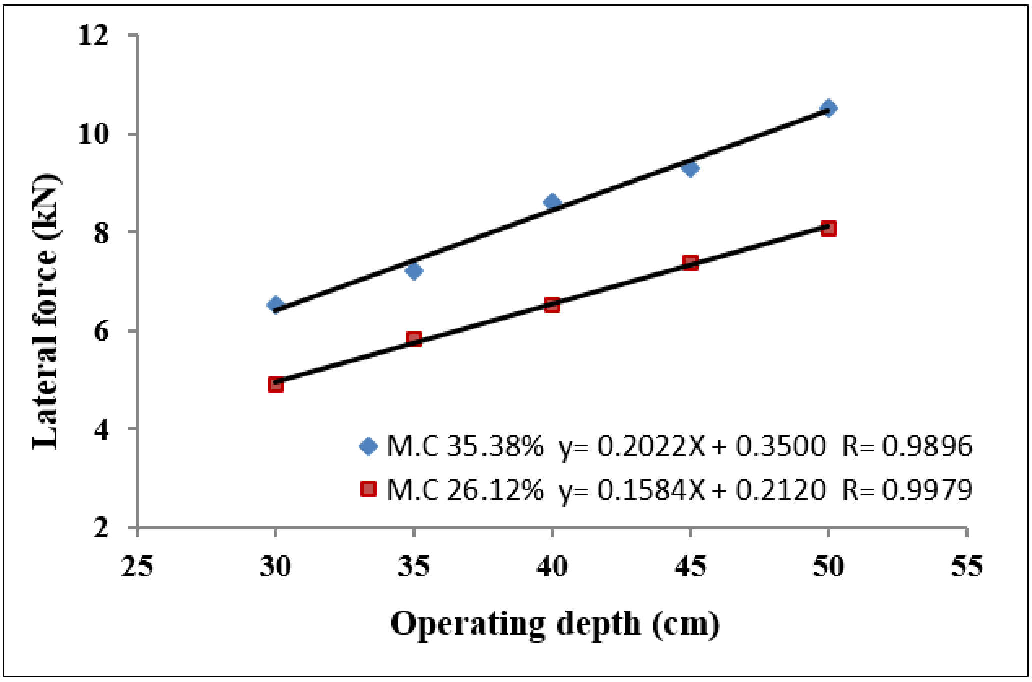

Fig. 5: The lateral force for LIMP versus the operating depth in two moisture content levels

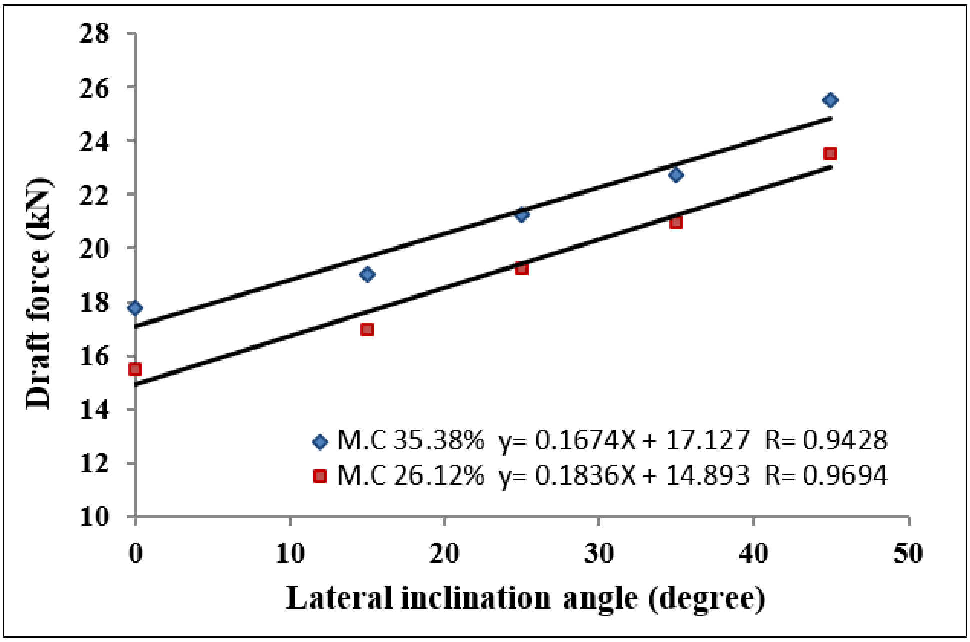

Fig. 6: The draft force versus the lateral inclination angle of LIMP for two moisture content levels

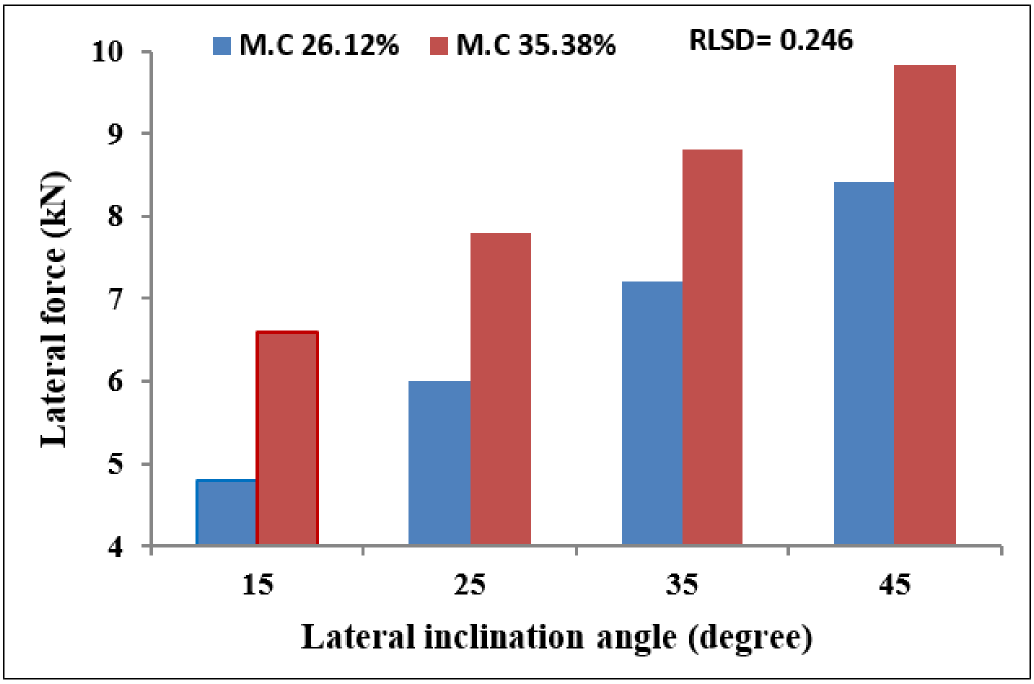

Fig. 7: The lateral force for LIMP versus the lateral inclination angles for two moisture content levels

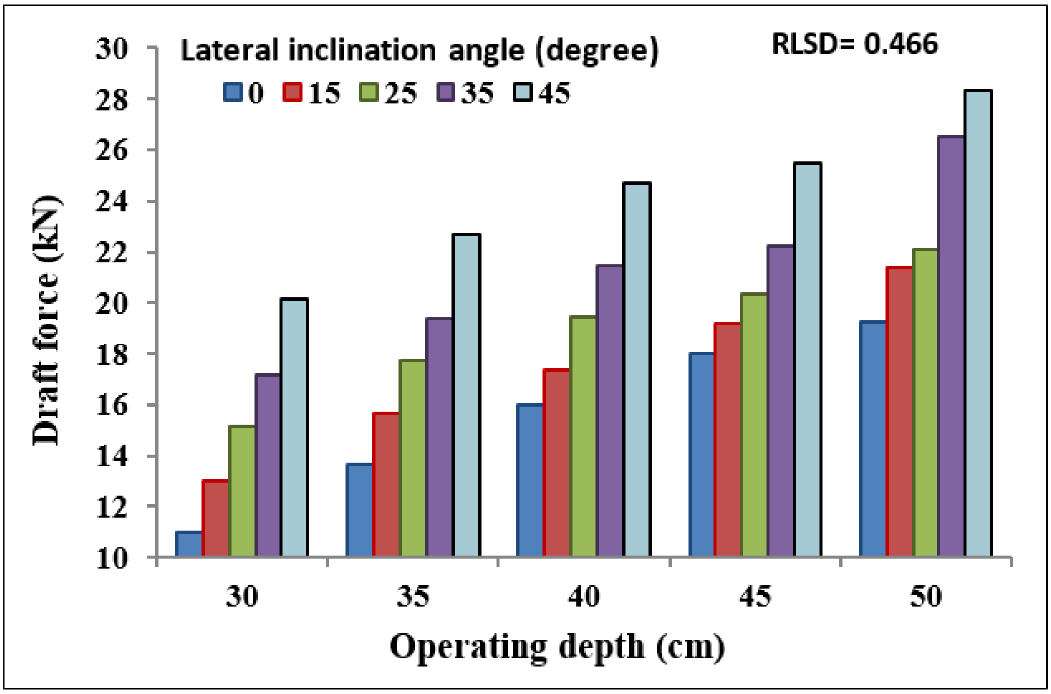

Fig. 8: The draft force versus the operating depth for CVMP and LIMP for different lateral inclination angles

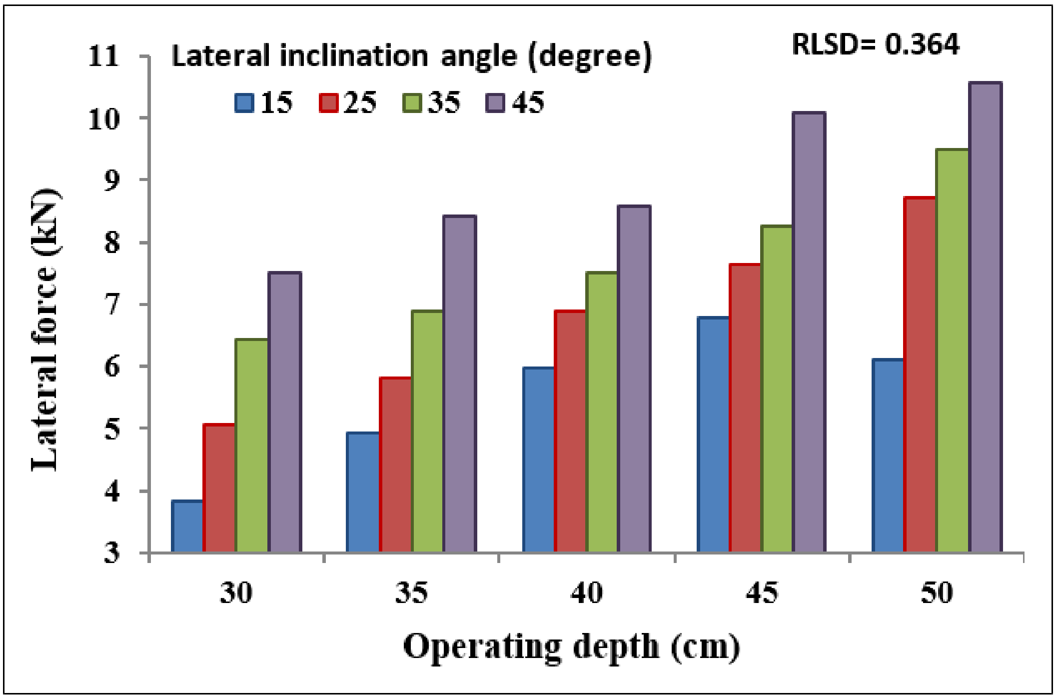

Fig. 9: The lateral force versus the operating depth for LIMP for different lateral inclination angles

Table (1): Initial physical and mechanical properties of soil.

Soil specifications	Soil 1 (M.C 26.12%)					Soil 2 (M.C 35.38%)				
Soil depth (cm)	0-10	10-20	20-30	30-40	40-50	0-10	10-20	20-30	30-40	40-50
Moisture Content (%)	16.83	18.31	28.72	32.51	34.24	25.40	29.12	36.88	42.32	43.20
Cone Index (kN m^{-2})	1469	1767	2499	3077	3519	1222	1667	2306	2875	3397
Bulk Density (Mg m^{-3})	1.25	1.21	1.28	1.30	1.48	1.30	1.28	1.31	1.40	1.50
Cohesion (kN m^{-2})	9.78	11.25	12.77	15.34	18.38	14.12	15.61	17.75	21.84	23.56
Angle of internal friction (Degree)	32.21	34.21	30.54	26.56	28.36	29.24	30.11	27.47	24.22	25.64
Angle of soil metal friction (Degree)	25.54					32.91				
Adhesion (kN m^{-2})	0.173					0.440				
Clay (g kg^{-1})	497									
Silt (g kg^{-1})	382									
Sand (g kg^{-1})	121									
Soil texture	Silt Clay									

Table (2): Analysis of variance (F. Value) for Draft force requirements and Lateral force

S.O.V	df	Draft force, kN	Lateral force, kN
Block	2	23.76**	10.19**
Soil moisture (A)	1	1263.93**	364.96**
Lateral inclination angle (B)	4	2189.00**	417.77**
Operating depth (C)	4	2773.30**	556.94**
A*B	4	5.63**	4.41**
A*C	4	7.42**	10.85**
B*C	16	2.58**	6.17**
A*B*C	16	2.32**	3.42**
Error	98	0.119	0.108
Total	149		

** Significant differences at level 0.01