DEFORMATION AND FORCE CHARACTERISTICS CAUSED BY INCLINED TINES IN LOAM SOIL WITH MOISTURE CONTENT BELOW LIQUID LIMIT

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ABSTRACT
Deformation and force characteristics caused by flat rigid tines (inclined at an angle of 50^0 to the horizontal soil surface) in loam soil with moisture content below the liquid limit were studied using a glass-sided soil bin. The tines moved in the soil bin in a quasi-static speed and the soil deformation was observed through the glass side of the soil bin. Strain gauge bonded L- shaped force transducers were used in recording soil forces. Three moisture content levels (viz 5.2%, 21% and 33.5% (d.b.)) were used.

The results obtained indicated that soil deformation and force characteristics for loam soils are greatly affected by variations in soil moisture content. For 5.2% and 21% soil moisture contents, deformation patterns were progressive shear types. Soil forces for these moisture content levels were cyclic in nature and generally did not differ in magnitude. The deformation process was in regular cycles resulting in corresponding periodic variations in the soil reactions on the tines. There were no distinct zones as described in the passive soil pressure theory. Plastic type of soil deformation was observed in 33.5% soil moisture content with comparative high corresponding soil forces whose periodicity died off.

Key words : Deformation, force characteristics, inclined tines, soil moisture

1.0 INTRODUCTION

One of the methods of reducing costs in tillage is through efficient design of tillage tools. These tools have for a long time been designed on a trial and error basis as the soil-tool interactions involved have not been defined and quantified. More research is still to be conducted to clearly understand the mechanics of the soil under the influence of agricultural tillage tools.

Classical soil failure theories which have been adapted from concepts used to describe soil behavior for civil engineering purposes have for quite sometime been relied on in various attempts to predict tillage forces under varying circumstances (Godwin and Spoor, 1977; Hettiaratchi and Reece, 1967, 1974, 1975; Perumpral *et al.* 1983; McKeys and Ali, 1977 and Stafford, 1981). The passive soil pressure and critical state soil failure theories have commonly been used in such cases. There has been increasing concern as regards to the suitability of these theories in solving the various problems experienced in agricultural engineering including changes in soils and their properties. Under civil engineering conditions, initial soil failure is all that is required as opposed to the need to predict continuous repeated failure in agricultural engineering. Soil failure patterns and their corresponding reactions form a basis for the development of tillage tools. High degree of accuracy in defining these soil failure patterns is therefore, of vital importance.

Soil failure patterns have been reported to vary with soil and tool parameters [1, 2, 9-23]. Soil moisture content in particular has been observed to be of strong effect on variations in soil failure patterns. The patterns have also been observed to be quite different from those assumed by the passive soil pressure theory. Major variations in force response to tool travel velocity have been reported under a wide range of soil moisture content in various soil types and tillage tools (Rajaram. and Gee-Clough, 1988; Salokhe and Pathak, 1992, 1993; Sharma *et al*, 1990, 1992 and Wismer and Luth, 1972) There is currently no theory available which can predict the variations. These observations seem to oppose the applications of the force prediction models developed on the basis of the classical soil mechanics theories in solving agricultural engineering problems. Consideration was mainly given to brittle failure and speed effects were neglected in the development of these models. Tillage machines are employed under various soil failure conditions and speed, hence ideal models should take all these into consideration.

Variations in soil failure patterns and their corresponding soil forces have been observed while working with flat rigid tines (Makanga, 1997 and Rajaram and Gee-Clough, 1988) as soil moisture contents were varied from dry to wet unsaturated conditions.

2.0 MATERIALS AND METHODS

Variations in soil failure and force characteristics caused by changes in soil moisture content were studied in a glass-sided soil bin with loam soil. All experiments were conducted at a constant speed of 3.0 mm/s. This quasi-static speed enabled a clear observation of the soil characteristics. Simple flat tines with 0.5 cm thickness

and of different aspect ratios (tine width/tine depth) as given in Table 1 were used.

The tines were all inclined to the horizontal soil surface at a rake angle of 50^0 measured in a clockwise direction with the soil level in the soil bin as a reference position.

Compacted loam soil at moisture content levels of 5.2, 21 and 33.5 % (d.b) was used for all the experiments. The relevant soil shear strength characteristics and consistency limits are given in Table 2. Soil failure patterns were observed through a glass window with dimensions of 97.5 cm x 15.1 cm on the side of the soil bin. A clear space of 20 cm height was provided above the horizontal soil surface for viewing the surcharge build-up in front of the tines. White grids of 1 cm x 1 cm were marked with the help of a special stencil and pressurised talcum powder on the soil surface at the window side. This was necessary for observation of deformation lines.

Two identical tines were used in this study, one at the glass side for purposes of observation of failure patterns and the other at the center of the soil bin where soil reactions were recorded. To ensure minimum soil-glass friction, the glass was lubricated using a silicon wax lubricant. This was verified by measuring soil reactions on the two tines. The tines were mounted on strain gauge bonded L-shaped force transducers which were in turn attached to the tine mounting unit. The magnitude of soil reactions was recorded and its characteristics matched with the observed soil deformation patterns. Tine movement was controlled by hydraulic valves. Strain amplifier, data-logger, computer and a printer comprised the main data acquisition and processing system. Forward speed was measured by a 10-turn rotary potentiometer mounted to the main frame.

A video and still camera were used for recording the soil failure patterns at any instant of tine travel which were thereafter correlated with corresponding tine forces. Soil failure patterns were analysed for shear/failure angles, forward rupture distance and surcharge profiles. The shear angles were directly measured from photographs of the soil failure patterns taken throughout the test. Soil forces data was in most cases given on per unit tine area basis for homogenization purposes. Periodic variations in force-time curves of the soil reactions for the three moisture content levels were analyzed in terms of wave length, peak to trough ratio and amplitude as shown in Figure 1. This was done for the horizontal forces only which in general are of major interest.

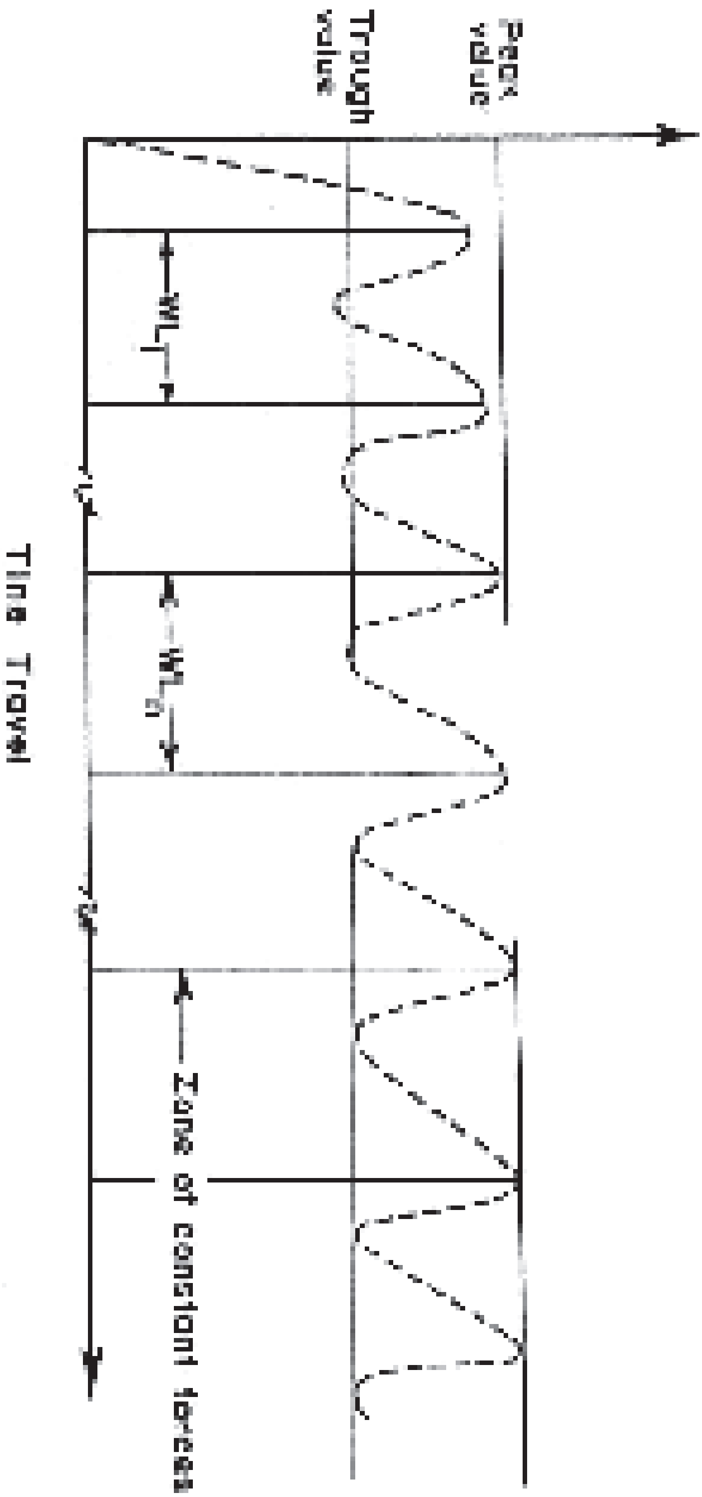

Figure 1: Definition of the parameters used in interpretation of variations in soil reactions

Ratio of peak to trough values of horizontal soil reaction averaged over all the failure cycles (R_r) $= \frac{\sum_{n=1}^{n_f} (\text{Peak value/Trough value})_n}{n_f}$

Amplitude of the horizontal soil reaction averaged over all the failure cycles (A_r) $= \frac{\sum_{n=1}^{n_f} (\text{Peak value} - \text{Trough value})_n}{n_f}$

Wavelength (WL) $= \frac{\sum_{n=1}^{n_f} WL_n}{n_f}$

Where n_f = Number of failure cycles in the test run
n = Failure cycle number

3.0 RESULTS AND DISCUSSION

3.1 Soil Deformation Characteristics at Different Moisture Levels

Progressive shear failure was observed in the dry soil with a 5.2% soil moisture content at all tine aspect ratios tested as previously reported by Spoor and Godwin, 1978. The failure characteristic for 21% moisture content level was basically the same as that observed at 5.2% soil moisture content. There was, however, an indication of the soil getting more compressed, particularly, at higher depths as implied by the closeness of the vertical grid lines observed through the glass window. The average failure angle (β) was in this case 31^0 which differed from the theoretical angle of $(45 - \phi/2)^0$ by 3^0 under this condition where ϕ was 22^0. This angle is close to the 32^0 angle observed in 5.2% moisture content. A difference of about 3^0 was also observed with the 5.2% moisture content which further confirms that the failure patterns are generally the same. During the experimentation process for 21% moisture content levels, the soil was observed to rise slowly along the tine face and the inclined shear surface. The rear portion eventually broke off, this time after a slightly longer time than it took with the 5.2% soil moisture content. Soil deformation patterns at the stage of dynamic stability were schematically represented by Figure 2 and the maximum rupture distance (r) predicted by the equation:

$$r = D \cdot (\text{Cot}\ \alpha + \text{Cot}\ \beta) \quad \text{--} \quad (1)$$

where,

D = Tine depth (cm)
α = Tine rake angle (degrees)
β = Failure angle (degrees)

Actual and predicted values of rupture distance are compared in figure 3 where there was no indication of major differences. A hyperbolic curve was fitted to this data and the equation defining this curve was given by:

$$r = ma^n \quad (2)$$

where,
r = maximum rupture distance per tine area, cm / cm^2
m = Constant
a = Tine aspect ratio (width / depth)
n = Power value to which "a" is raised

The m, n and the square of the coefficient of correlation values for the measured data were 0.17, -0.23 and 0.63 respectively while those for the predicted data were 0.19, -0.60 and 0.90 respectively. There was no soil disturbance below the tine tip, neither were there any transition soil zones as assumed by the conventional soil pressure theories.

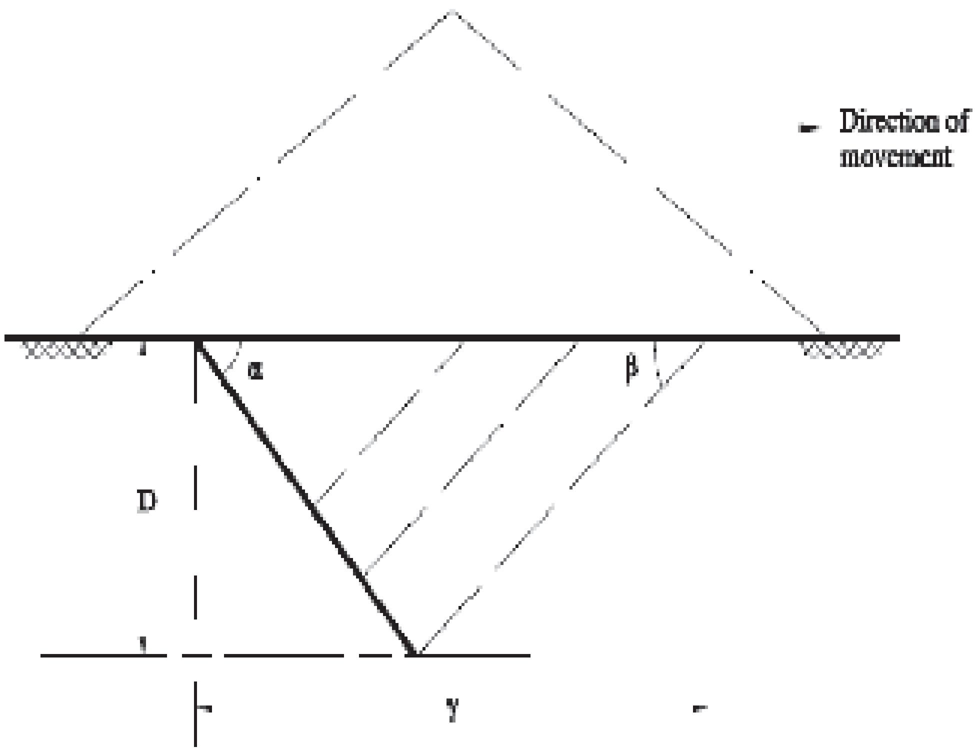

Figure 2: Schematic representation of soil formation patterns caused by a 50 deg rake angle, 10cm wide and 12cm deep at a 21% (d.b.) soil moisture content

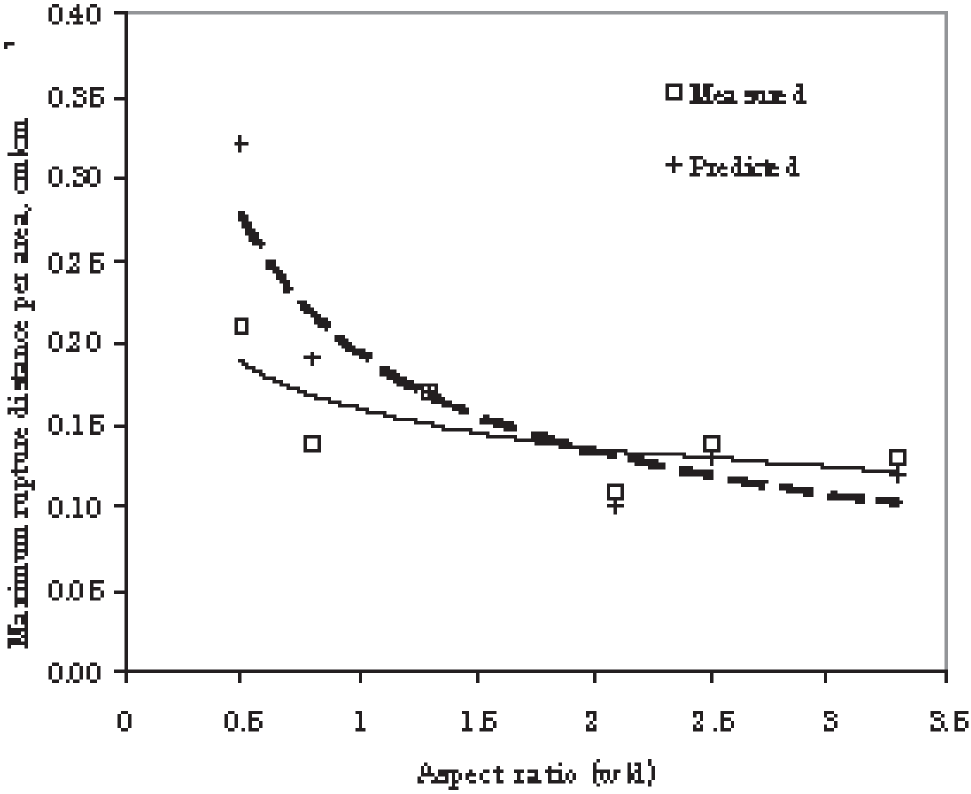

Figure 3: Comparison of actual and predicted maximum rapture distances for a 50 deg rake angle tines operating in a 21% (d.b.) moisture content loam soil

Observations for 33.5% soil moisture content level were quite different from those at 5.2% and 21% soil moisture levels. For all tine aspect ratios studied plastic like mass of soil started rising up to form the surcharge a few seconds after the tine started moving forward. The soil moved up the tine surface. Instead of the inclined shear lines observed in the other moisture contents, there was a clear indication of the soil getting compressed in the region in front of the tine tip and above it. This was evidenced by the closeness of the vertical grid lines near the tine tip and the region above and slightly ahead. Details of this are contained in Makanga .,(1997). Even though small cracks could be seen in some cases, the soil mass did not totally break up into lumps but instead kept on coiling in front of the L-shaped force transducer.

The failure pattern observed after about 100 mm of tine travel in this study consisted of four distinct zones shown as 1–4 and respectively known as 'no distortion', 'distortion','distortion attenuating' and 'undisturbed' zones as shown in figure 4. In the no distortion zone, the soil was not compressed enough to cause any remarkable visibility of distortion in the grid in spite of adequate force to move the soil into the surcharge zone. The distortion zone was an area of highly compressed soil as indicated by the closeness of the vertical grid lines observed through the glass window. In the distortion attenuating zone, there was less distortion of the vertical grid lines (less soil compression particularly to its right side). The undisturbed zone was an area of no compression and no movement i.e. there was no effect of tine force and movement.

3.2 Soil Force Characteristics at Different Moisture Levels

Soil force characteristics for all moisture content levels studied showed that the horizontal and vertical forces were cyclic in nature and in phase. The cyclicity could be related to the observed intervaling of the soil deformation patterns at different stages of tine travel (Spoor and Godwin , 1978) and were analysed for ratio of peak to trough values (R_{ac}), wave length (WL) and amplitude (A_{ac}). The magnitudes of the force-distance curves were affected by variations in soil conditions which were difficult to avoid even by most careful soil preparation. The reasons for the gradual building up and eventual attaining of dynamic stability of the force-time curves is a result of the corresponding behavior of the soil surcharge Sharma, *et.al,* 1992; Spoor and Godwin and Stafford 1981).

Figure 5 shows a force-time curve for a tine operating at 5.2% moisture level, while Figure 6 shows that for the 21% moisture level. Comparison of the results does not reveal any major differences in the periodic behavior of the forces at the two different moisture levels. Figure 7 shows a force-time curve for a tine operated at 33.5% moisture level. The forces were quite high but with a dying off periodicity. The effect of soil moisture content on soil reactions is also shown in Figure 8 which apparently shows the effect of tine aspect ratio. The results indicate that raising the moisture content from 21% to 33.5% increases the soil reactions five times. Hyperbolic curves fitted on the data yielded the following equation:

$$D = ma^n \qquad (3)$$

where,

D = Draft per unit area, N/cm^2
m = Constant
a = Tine aspect ratio (width/depth)
n = Power value to which "a" is raised

The respective m, n and the square of the coefficient of correlation (R^2) values are given in Table 3. The effect of tine aspect ratio was earlier on investigated and reported to be resulting from changes in the respective tine widths and depths [8].

The results of the interpretations of the force-time curves for variations in moisture contents are presented in Figures 9 through 11. Higher peak to trough values were observed in 5.2% and 21% moisture contents (Figure 9). Straight line relationships were fitted in this set of data. The equation defining these relationships was given by:

$$R_{ac} = c + ma \qquad (4)$$

where,

R = Peak to trough ratio of draft (10^{-2}) per unit tine area.

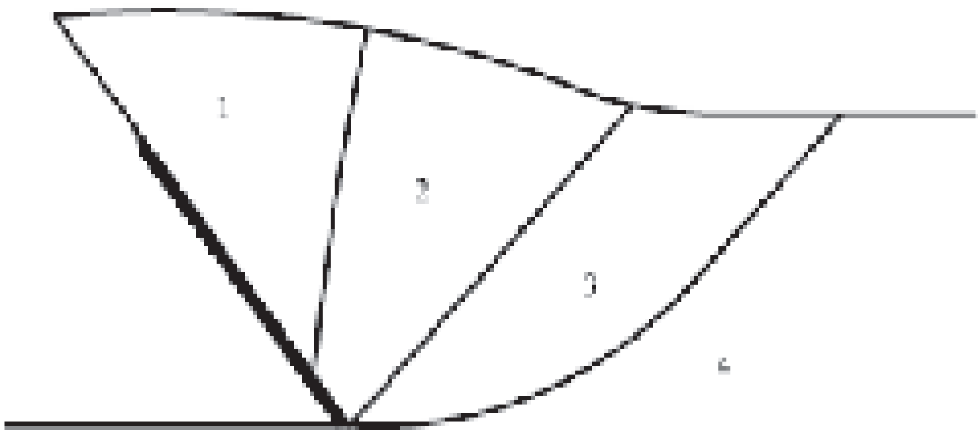

Figure 4: An illustration of the soil failure zones caused by 50 deg rake angle tines in a 33.5% (d.b.) moisture content loam soil after 10 cm tine travel.

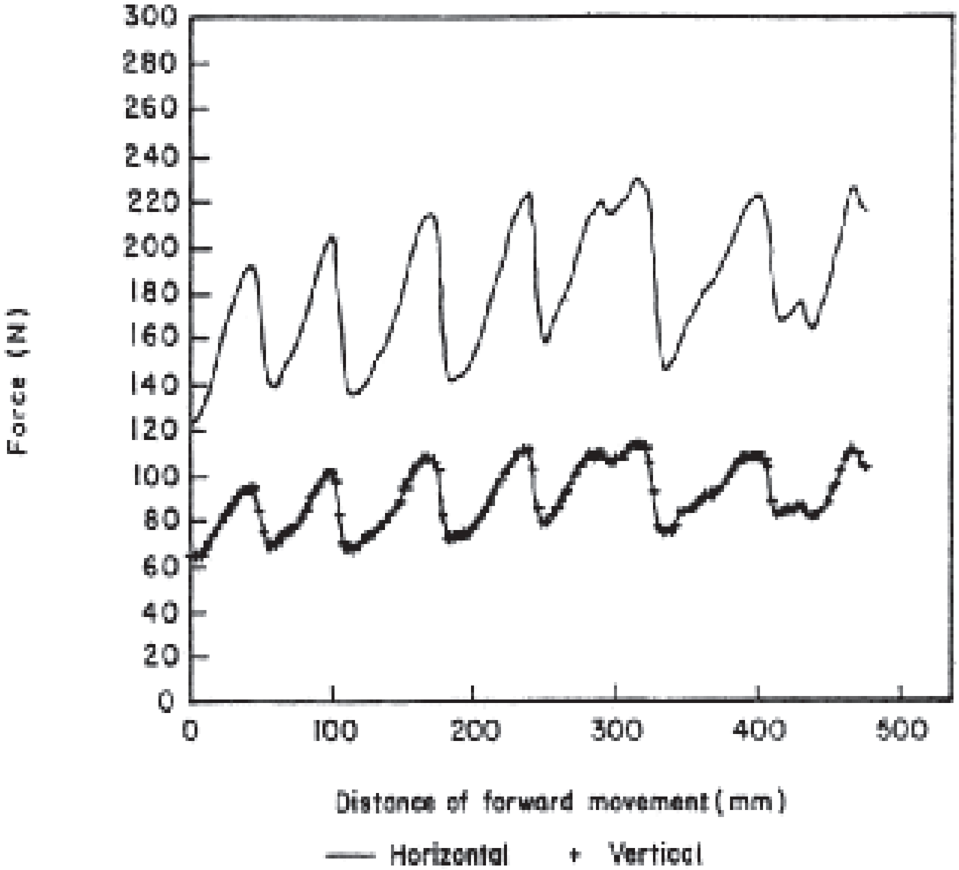

Figure 5: Force-distance curves for a tine of 10cm width, 12 cm depth and 50 deg rake angle operating ina 5.2% (d.b.) soil moisture

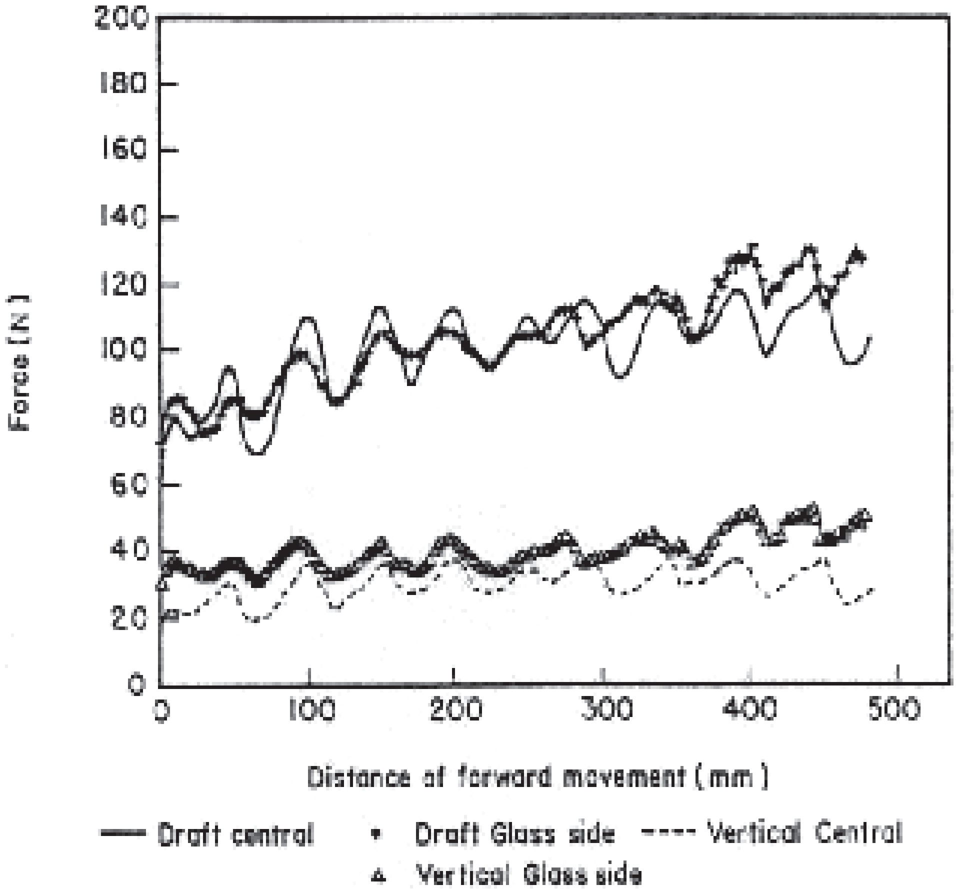

Figure 6: Force-distance curves for a tine of 11.25 cm width, 9 cm depth and 50 deg rake angle operating in a 21 %(d.b.) Soil moisture content

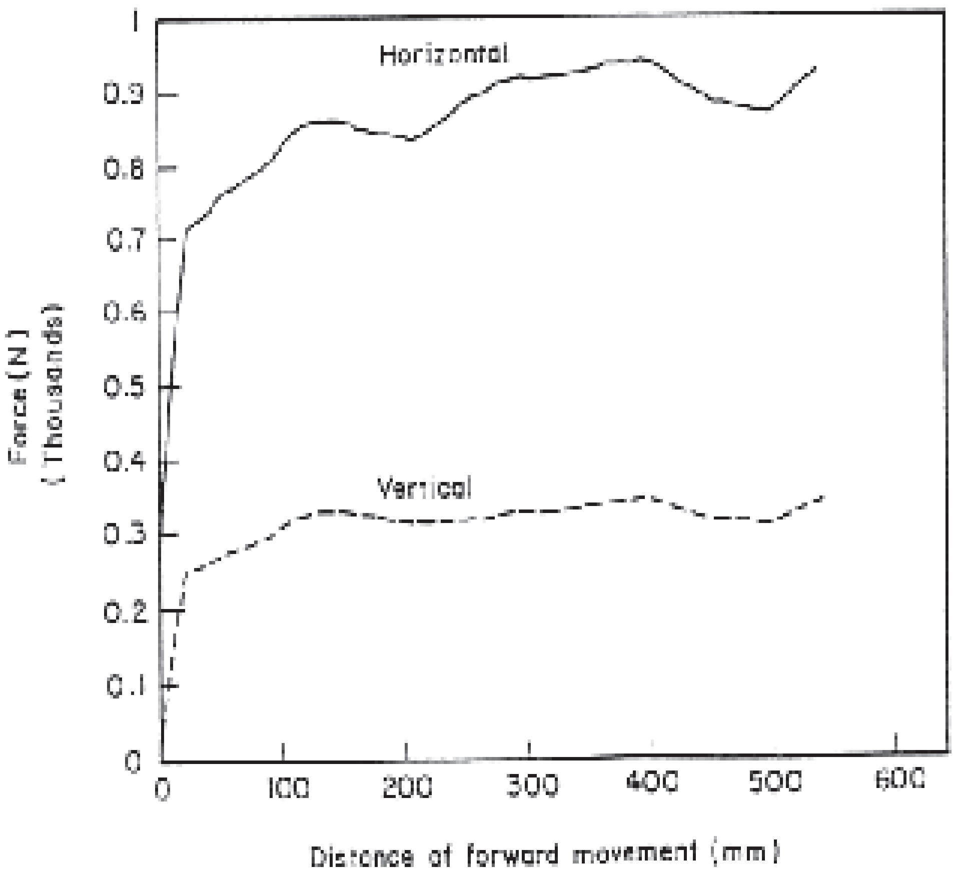

Figure 7: Force-distance curves for a tine of 11.25 cm width, 9 cm depth and 50 deg rake angle operating in a 33.5% (d.b.) soil moisture content

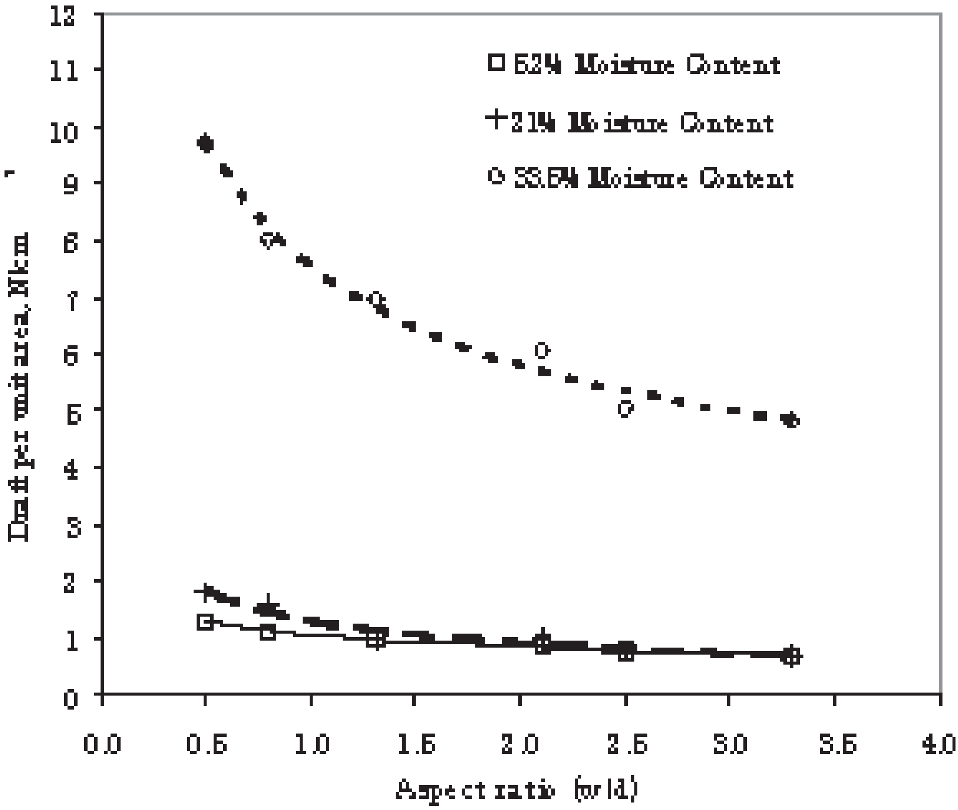

Figure 8: Relationship between draft force per unit tine area and ratio aspect for various soil moisture contents (rake angle = 50 deg)

The respective c, m and R^2 values are given in Table 4. The force-distancecurves for 5.2% and 21% moisture contents indicated that periodicity persisted and hence differences in peak and trough values were higher compared to those observed in 33.5% moisture content where periodicity had started dying off. Figure 10 shows the effect of moisture content and aspect ratio on wave length of draft force per unit tine area. There was generally no definite trend. Wave lengths for 5.2% and 21% were lower and almost the same. Periodicity persisted in these cases and hence there were comparatively many failure numbers per given time and therefore lower wave lengths. In the case of the 33.5% moisture content, the periodicity was dying off which meant fewer peaks and troughs per given time hence higher wave lengths. The effect of moisture content and aspect ratio on amplitude of draft force per unit tine area is shown on Figure 11. Amplitudes for 5.2% and 21% moisture contents were lower and almost the same since soil reactions in these cases were comparatively lower. Hyperbolic curves seemed to fit fairly well for this data and equation 3 can be used to define these curves. The corresponding m, n and R^2 values are given on Table 5. For the 33.5% moisture content, soil reactions were quite high and even though periodicity was dying off, the differences between peak and trough figures were high. This accounted for the higher amplitude figures. A straight line relationship defined by equation 4 seemed to fit this data even though the R^2 value was quite low (0.37). The c and m values were 0.65 and –0.032 respectively. The observed variations in soil force characteristics at different soil moisture levels are mainly due to corresponding changes in cohesion and adhesion.

The various results and discussion presented in this study indicate that soil failure patterns and their corresponding reactions are affected by variations in moisture content and tool design parameters. The failure patterns correlate quite well with their corresponding soil reactions. Correlation of these observations with previous research (Makanga, ., 1997; Makanga, *et. al*, 1996 and 1997, Rajaram and Gee-Clough, 1988; Salokhe and Gee-Clough, 1987, 1987a and 1988) shows that the effect of moisture content is well pronounced in cohesive and cohesive-frictional (loam) soils particularly within the plastic range. Previous and present studies therefore indicate that clay and loam soils basically have the same trend of failure patterns but with differences in force magnitudes. Frictional soil (sand) failure patterns are mainly affected by tool design parameters (Salokhe and Pathak 1992 and 1993; Sharma *et al*., 1990 and 1992).

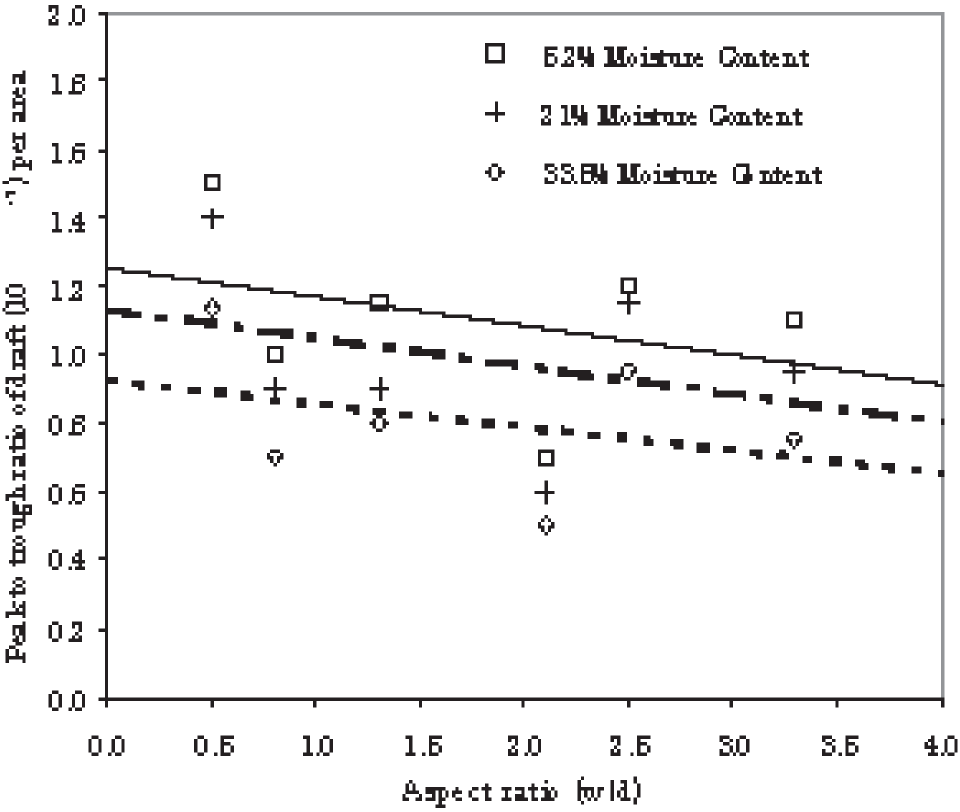

Figure 9: Relationship between peak to trough ratio of draft force per unit area and aspect ratio at different soil moisture contents (rake angle = 50 deg)

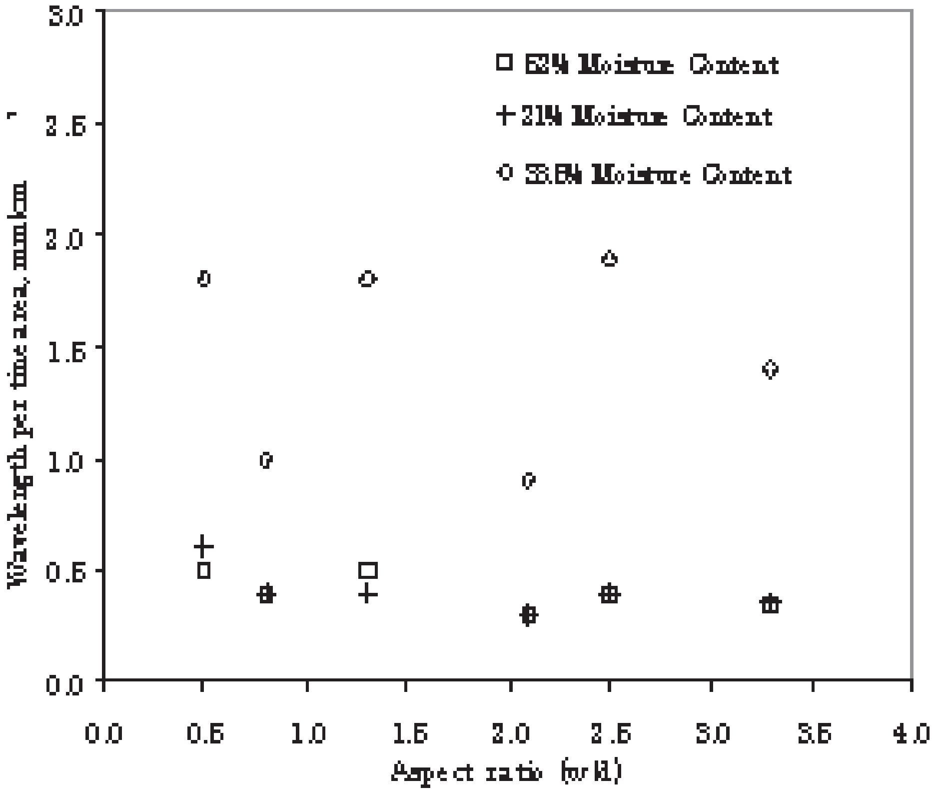

Figure 10: Relationship between wavelength of draft force per unit tine area and aspect ration at different soil moisture contents (rake angle = 50 deg)

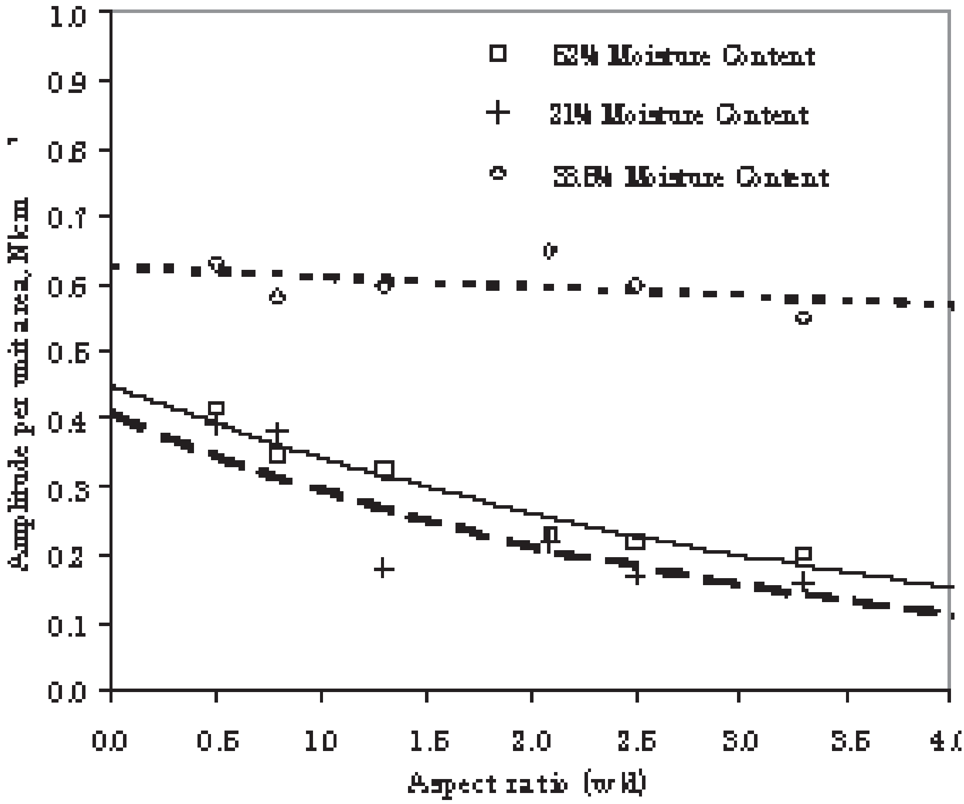

Figure 11: Relationship between amplitude of draft force per unit tine area and aspect ratio at different soil moisture content (rake angle = 50 deg)

4.0 CONCLUSION

The observations from this study indicated that soil deformation patterns are affected by variations in tine design parameters and moisture content. Progressive shear failure was observed in dry soil (5.2% moisture content) in all the three angles studied with variations in each angle. Soil deformation patterns by 50^0 rake angle tines consisted of inclined shear lines starting from the tine tip and gradually moving upwards towards the horizontal soil surface intersecting it at an average failure angle of 32^0. In the case of a 90^0 rake angle, the inclined shear line was at a distance from the tine tip and the average failure angle was 31^0. Formation of prismatic shaped soil wedges, which remained stationary throughout the tine travel, was observed while using a backward raked 130^0 rake angle tines. The soil deformation patterns in all the three cases were periodic and correlated quite well with the corresponding soil reactions. Investigation on individual effect of width and depth revealed that the apparent effect of aspect ratio on soil deformation patterns, their corresponding soil reactions, forward rupture and surcharge profiles is in fact mainly due to variations in width and depth. Soil deformation patterns for 21% moisture content were basically the same as those for for 5.2% moisture content except for a rise in their corresponding soil reactions. Plastic type of failure was observed in 33.5% moisture content with very high corresponding soil reactions whose periodicity was dying off. Rises in soil reactions with increase in moisture content was found to be a result of increase in soil cohesion and adhesion. The soil reactions (horizontal and vertical) were cyclic in nature and in phase as observed from the force-time curves. They matched quite well with the soil deformation patterns and again, variations in their wave length, peak to trough ratio and amplitude was mainly due to changes in width and depth and not just the aspect ratio.

The observations of this study indicate that soil deformation patterns and their corresponding reactions are mainly affected by moisture content and tool width and depth. One of the methods of reducing costs in tillage is through efficient design of tillage tools/implements. These tools have for a long time been designed on a trial and error basis as the soil-tool interactions involved have not been well defined and quantified. This study has shown deformation and force characteristics for loam soils at different moisture level and tool aspect ratio. This is a vital information which should contribute towars efficient design of tillage machinery based on soil-tool interactions and not on classical soil mechanics theories which might not be applicable under all tillage and general earthmoving conditions. This is important particularly in view of the fact that soil is a very dynamic engineering material.

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Table 1: Specifications of the tines used.

Width (w) (cm)	Depth (d) (cm)	Aspect ratio (w/d)
6	12	0.5
10	12	0.8
11.25	9	1.3
18.75	9	2.1
15	6	2.5
20	6	3.3

Table 2: Soil-shear strength characteristics and consistency limits

(a) Soil-shear strength characteristics

Moisture content (%d.b)	Cohesion (kPa)	Angle of internal friction (deg.)	Adhesion (kPa)	Soil-metal friction angle (deg.)	Cone index (kPa)	Specific weight (gm/cc)
5.2	0.02	20.0	0.005	10.0	210.0	1.2
21.0	0.20	22.0	0.035	10.0	258.0	1.3
33.5	7.40	19.3	0.460	12.0	422.0	1.7

(b) Consistency limits

Plastic limit	23%
Liquid limit	51%
Plasticity Index	28

Table 3: m, n and R^2 values for Fig. 8

Soil moisture content (% d.b.)	m	n	R^2
5.2	1.03	- 0.43	0.99
21.0	1.22	- 0.59	0.91
33.5	7.43	- 0.42	0.98

Table 4: c, m and R^2 values for Fig. 9

Soil moisture content % (d.b.)	c	m	R^2
5.2	0.21	- 0.87	0.88
21.0	0.21	- 0.87	0.88
33.5	0.08	- 0.72	0. 96

Table 5: m, n and R^2 values for soil moisture contents of 5.2% and 21% (d.b.) in Fig. 11

Soil moisture content % (d.b.)	m	n	R^2
5.2	0.32	- 0.42	0.93
21.0	0.28	- 0.52	0.87

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Fig. 6: Force-distance curves for a tine of 11.25 cm width, 9 cm depth and 50 deg. rake angle operating in a 21% (d.b.) moisture content soil.

Fig. 7: Force-distance curves for a tine of 11.25 cm width, 9 cm depth and 50 deg. rake angle operating in a 33.5% (d.b.) moisture content soil.

Fig. 8: Relationship between draft force per unit tine area and aspect ratio for various soil moisture contents (rake angle = 50 deg.).

Fig. 9: Relationship between peak to trough ratio of draft force per unit area and aspect ratio at different soil moisture contents (rake angle = 50 deg.).

Fig. 10: Relationship between wave length of draft force per unit tine area and aspect ratio at different soil moisture contents (rake angle = 50 deg.), (- - 5.2%, - + - 21% and - ◊ - 33.5%).

Fig. 11: Relationship between amplitude of draft force per unit tine area and aspect ratio at different soil moisture contents (rake angle = 50 deg.), (- ν - 5.2%, - + - 21% and - ◊ - 33.5%).

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