SOIL FAILURE CRESCENT RADII MEASUREMENT FOR DRAFT IN TILLAGE STUDY

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ABSTRACT

Field clay loam and sandy loam soils were tilled with a chisel shaped tine at different tillage geometries. Soil cracks and the extent of their propagations in the front and to the sides of the tillage tool were observed and measured. These measurements provided the failure crescent radii and the soil furrow geometry used in calculating the draft during tillage. The effects of the tillage tool width, rake angle and depth in the soil on the draft were statistically Significant at the 5% level and higher in the clay loam and sandy loam soils.

From the established empirical relationships between the draft and the tillage tool geometry, it was possible to recommend a tillage tool geometry which would minimise draft during tillage.

NOTATIONS

C = Cohesion

d = depth of tillage

= depth of surcharge on soil free surface

H = Total blade force made up of P and V components

Nc = Cohesive coefficient in the earth- moving equation

Nq = Surcharge coefficient in earth moving equation

N_{γ_ε} = Soil unit weight coefficient in the earth moving equation

P = Draft force

q = Surcharge on soil free surface=Υ_h

Q = Total surcharge

r = radius of failure crescent

s = effective width of the failure crescent

V = vertical component of blade force

V = width of blade

α = blade rate angle

δ = soil metal friction angle

Υs = soil unit wei.ght

ϕ = soil internal friction angle

φ = angle of the crescent radius

β = inclination of the failure plane to the horizontal

1. INTRODUCTION

The draft experienced in plowing varies with the construction of the implement and the type and condition of the soil plowed. Whenever an appreciable amount of draft is absorbed by the tractor, it makes steering and plowing operations more difficult for the tractor operator. While it is wasteful of tractor power and the driver's time to work a width appreciably less than the tractor can handle at a suitable forward speed, it is, however worse management to attempt to work at a width that is beyond the tractor's drawbar pull in the conditions prevail1ng (1).

The depth of tillage, implement width and rake angle influence the area of sell disturbed (2, 3). Furthermore, as pointed out by Spoor and Godwin (4), the soil disturbance created by one tine is closely related to the soil shearing resistance. Spoor and Godwin also observed that the area of soil disturbed increase with the increase in the blade sweep angle.

The reaction of the soil to a moving blade is easily understood when the force relations in a soil failure plane are simplified. The tool causes failure of the soil and the fundamental characteristic of the action is a repeated failure of the soil by shear which forms small blocks of soil. Payne (5) derived from the passive earth pressure theory, the total pressure per unit width of a moving blade in the form:

$$P = 1/2\, Yd^2\, tan^2 \left(\frac{\pi\emptyset}{42}\right) + 2cd\ tan \left(\frac{\pi\emptyset}{42}\right) \qquad (1)$$

The above equation was for an ideal highly polished tine moving in a frictional-cohesive soil. Payne (ibid) also studied real conditions in which the soil-metal frictional angles were not negligible.

Following the work of Payne, a lot of further developments in the analysis of the mechanics of tillage tools have been carried out by other workers (Osman (6), Reece (7), Sokolovski (8), Hettiaratchi, et al, (9), Mckyes (10), Ali and Mckyes (11) Negi, et al (12), Mckyes and Ali (13). Mckyes and Ali (13)) based on the previous work of Reece (7) and Hettiaratchi et al (9) proposed a soil failure model for narrow blades. They assumed that the failure boundary from the tip of the blade to the surface could be represented by straight lines rather than the log spirals. These approximate straight lines were assumed to make an unknown angle B with the horizontal. Their subsequent technique was to apply the mechanics of equilibrium and impending soil failure on the boundaries of the three dimensional soil segments ahead of the blade to arrive at the draft force. They analysed the forces on the two dimensional centre section and the total horizontal forward force from each of the side crescents of the three dimensional failure zone. The modified earth moving equation proposed by Mckyes and All was:

$$H = \left\{\gamma\, d^2 \frac{rw}{3wd}\left(1 + \frac{2rd}{3dw}\sin Q\right) + cdw\,(1 + \cot(\beta + \phi))\right\}\left\{1 + \frac{rd}{dw}\sin Q + qwd\left\{1 + \frac{rd}{dw}\right\}\right\}$$

$$\left\{\frac{1}{cot(a+\delta)+cot(B+\phi)}\right\}$$

The tillage tool geometry and the so failure model have been schematically illustrated in Figs. 1 and 2. Mckyes and Ali (13) showed that the calculate draft force was a function of the unknown angle as well as the relevant soil properties. Following the principle that the soil failed on the path of least resistance, they suggested that the force function could be minimized with respect to β

The expression in equation (1) is recognizable as similar to the one originally proposed by Reece (7) in the simplified form.

$$P = (\Upsilon_s\, d^2 N\Upsilon_s + dNc + qdNq)\, W \qquad (2)$$

The identifiable coefficients in the analytical equation (1) are:

$$N_s = \frac{\frac{r}{2d}\ 1 + \frac{2r}{3d}\underline{d}\sin}{\cot(a+\delta)+\cot(+)} \qquad (3)$$

$$Nc = \frac{\{1+cot\beta\cot(B+\emptyset)\}\left\{1+\frac{rd}{dw}\sin\emptyset\right\}}{\cot(a+\delta)+\cot(B+\emptyset)} \qquad (4)$$

$$\frac{N_{q = \frac{r}{d}\left\{1+\frac{rd}{dw}\sin\wp\right\}}}{\cot(a+\delta)+\cot(B+\emptyset)} \qquad (5)$$

Negi, et al, 12 reported that the as chosen by Mckyes and Ali (13) for the minimum Nϒ in equation (3) was by trial and error. Furthermore, Desir (2) observed that the use of the minimization procedure limited the range of application of the analytical mechanics approach. In effect the straight line failure model proposed by Mckyes and Ali (3) was a three dimensional variation on the method of trial wedged in classical soil mechanics solutions of two dimensional earth work failure analyses

The review of research work on draft forces and soil failure geometry of cutting blades showed a reasonable gain in confidence in predicting forces on blades of simple shapes and in estimating the volume of soil cut (10). Unfortunately, the models and the theoretical equations seem so complex that the tillage tool user who is not very knowledgeable in the applications of analytical mechanics would still need a simpler model to quickly appreciate the contributions of the tool geometry to the development of draft in the field. The objectives of this study, therefore included the field measurement of the failure crescent radius following the model approach of Mckyes and Ali (13), the use of the measured failure crescent radius to determine the significant relationship between the tillage tool geometry and the calculated draft, to provide information on the soil behaviour, during tillage and to statistically establish a simple model relationship between the tillage tool geometry and the draft calculated from the measure of the Soil disturbance in the field. The statistical significance of the models would be useful in predicting draft variations from different tillage tool geometry.

2. METHODS AND MATERIALS

Chisel shaped tines of 6.3cm, 12.7cm and 20.3cm widths at rake angles of 20^0, 25^0, 30^0 and 35^0 were constructed to operate at 15.0cm and 25.0cm depths of tillage. The tillage implements were constructed in the Department of Agricultural Engineering of McGill University, Montreal, Canada (14). The random combination of the tillage tool geometries provided 24 experimental treatment combinations. The treatment combinations were randomized into rectangular field plots in a clay loam and a sandy loam soil at the Macdonald campus of McGill University, ste Anne de Bellevue, Quebec, Canada. The plots in each soil were laid out in a randomized complete block design of three blocks. In each field a control treatment plot of zero tillage was added to each block for comparative purposes. Each block consisted of the 24 treatment plots and a zero tillage control plot. The blocks also corresponded to three soil moisture content ranges which resulted from the periodic spacing out of the experiments in the blocks.

The pre-tillage disturbances in the fields were significantly minimized. Each field was mown, marked out and left undisturbed for a reasonable period to the tillage. The in situ soil densities in each plot were determined before and after the tillage operation by the use of a direct transmission gamma ray radioactive moisture density gauge.

The corresponding moisture contents were determined by core sampling. The tillage operation was done on each marked plot using the corresponding tillage tool geometrical combination.

Each tillage operation was started from one end of the plot and continued to a distance of 5m before stopping. At the moment of stopping the blade was left at the depth of tillage in the soil and any surcharge that must have been built up on the shank was gently removed. The soil cracks and the extent of their propagations in the front and to the sides of the tillage tool were observed and measured with a graduated tape. These measurements provided the radii of the failure crescents.

The blade was gently lifted from the depth of operation in the soil until the contents of the soil disturbance in the front and to the sides of the tool became clearer and more visible than before. The extents of soil disturbance were again measured in the front and to the sides of the tillage tool. The blade was then lifted completely to the soil surface. The depth of the furrow, its widths and the forward and side failure distance of the soil from the edges of the blade were measured. The measured depths and widths were to confirm the treatment combination specifications for each plot.

The tillage operation along the plot was resumed at a reasonable distance of one metre from the last point of measurements. At this second stage of tillage the furrow measurements were done as soon as the blade had reached the required depth of tillage and there was no noticeable surcharge formed on the Shank. At the completion of the measurements the tillage operation was resumed from that point at which the measurements were made. Before lifting the tillage blade from its depth of operation in the soil the third set of the measurements of the extent of the soil disturbance were made at the end of the plot.

Other soil tests which were done included torsion shear tests using grousered shear annulus in the furrow to determine such soil shear strength parameters as the internal friction angle, the cohesion and the soil-metal friction angle. The sets of furrow measurement were compared and averaged. At the end of a plot run, the tractor and the tillage tool in a transportation position were steered carefully into a turn trip after necessary changes had been made in the geometry of the tillage tool.

3. RESULTS AND DISCUSSIONS

The characteristics of the field soil behaviour dur1ng the tillage operations varied from one experimental block to another and from one soil to another. These characteristics which were in the form of crack formations and the extent of the soil disturbances were observed during the process of the measurement of the failure crescent (Figs. 3 to 6). The photographing of the crack propagation was with the aid of an Automatic Power Winding Canon Camera. The tracks and their directions were however, very unstable and would not be easily visible unless the tillage operation was done slowly.

In the clay loam soil, it was observed that as the blade penetrate into the firm soil, cracks were initiated. The cracks extended in a near horizontal direction, thus clearing the path for the blade edge. In the granular sandy loam, the fine grain sizes inhibited the crack propagation because of the lack of continuity in the cleavage planes of the large contiguous grains. What was generally visible in the two soils was a successive development of lifted soil failure wedges by the moving blade. The lifted wedges with fissure present slid forwards and upwards along the blade surface. The movements of the wedges were visible at the soil surface when the fissures widened and the soil matrix moving blade. The lifting and sliding of the soil was higher than that of the original unloosened soil or that of the adjacent untilled soil.

The forward rupture distances were observed to increase in the rake angle of the tillage blade and with the increase in the depth of tillage. The elongation of the limit of the crescent with the decrease in the rake angle of the tillage blade was observed to be due partly to the change in the position of the bottom leading tip of the blade relative to its line of emergence. Thus, the radius of the failure crescent was related to the draft required to produce the soil disturbance and loosening during the passage of the blade because it was observed that the extent of the crescent radius was a function of the volume of the soil disturbed.

In using the field physical measurement procedure in determining the radius of the failure crescent, it was observed that reasonably high coefficients of correlation (r = 0.82 for the sandy loam and (r = 0.99 for the clay loam) were obtained in relating the calculated draft to a dynamometer measured draft (14).

In order to calculate the draft using equation (2), the surcharge was assumed to be zero and thus Nq was zero. The equation thus reduced to

$$P = (\Upsilon s d^2 N\Upsilon s + cdNc) \quad (6)$$

The calculated drafts using equation (6) for each treatment plot were statistically related to the tillage tool geometry. In Table 1, the statistical analyses showed that the effects of the width of the tillage blade, the rake angle, and the depth of tillage on the draft in the clay loam and sandy loam were highly significant at the one percent level. The effects of the interactions of the tillage tool geometry were highly significant at ·the 5%level and higher. The significance of the field measurements was again evident in the Duncan's new multiple range tests on the means of the-drafts, as shown in Tables 2 and 3.

From the above statistical evidences, it was therefore reasonable to infer that the raft utilized in a field tillage would be predictable from a model that relates the draft directly to the rake angle, blade width and depth of tillage

The polynomial regression equations developed to relate the tillage tool geometry to the draft were:

$$P = 5.730 + 121.130wd + 6.133w - 20.090\alpha\ 25.371\alpha \quad (7)$$

for the clay loam; and

$$-10.773 + 200.382wd - 17.361w + 52.555\alpha - 51.738\alpha \quad (8)$$

for the sandy loam, with P in KN, α in radians, w and d in metres.

These models represent a further simplification the understanding and use of the previously developed earthmoving equations. Whereas, there would be the need to recalculate Nϒs, NC and possibly Nq in equations 2 to 5 during a variation of the tillage tool geometry for the prediction of draft values, such a need would be unnecessary in the use of equations 7 and 8. In order to use equations 7 and 8, preliminary studies would be necessary to determine the polynomial regression coefficients for the particular soil. Once the regression coefficients had been determined, the dependent variable would be predicted from the use of any of the independent variables in equations 7 and 8. Therefore the advantage in the use of equations 7 3 and 8 is that the steps required to predict the draft during tillage have been reasonably reduced. An extension staff or someone knowledgeable in analytical mechanics could carry out the preliminary studies to provide the regression coefficients for the tillage tool user. The rest of the prediction exercise would just be the direct application of the rake angle, blade width and depth of tillage into the equivalent of equation 7 or 8. The significance of equations 7 and 8 were evident from the relatively high coefficients of determination shown in Table 4.

In Fig. 7, the draft in the clay loam increased curvilinearly with the increase in the rake angle of a tillage blade of a certain width and at a certain depth of tillage. In Fig. 8, the draft in the clay loam increased with the increase in the width of a tillage blade of a certain rake angle and at a certain depth of tillage. For a tillage blade of a certain width and rake, angle, the draft in the clay loam increased with the increase in the depth of tillage (Figs. 7 and 8). In Fig. 9, the draft in the sandy loam increased curvilinearly up to a point with the increase in the rake angle of a tillage blade of a certain width and at a certain depth of tillage. Above that point of maximum draft, the draft decreased curvilinearly with the increase in the rake angle of the tillage blade. The point of maximum drat was between 290 and 31 rake angle of tillage blade. In Fig. 10, the draft in the sandy loam increased with the increase in the width of a tillage blade of a certain rake angle at a certain depth of tillage. For a tillage blade of a certain width and rake angle the draft in the sandy loam increased with the increase in the depth of the tillage (Figs. 9 and 10).

Some of the above relationships agreed with the observations recorded in the study. Some of the observations seemed to be substantiated by the findings of Spoor (15) and Mckyes (10) in the other related soil tillage mechanic studies. Spoor suggested that the increase in soil compaction with rake angle of a tillage blade increased the bulk shear strength of a soil. The above increase in the shear strength at the soil also increased the draft required to move the blade of a large rake angle through the soil. Mcktyes explained that tile increase in the rake angle of a blade increase the soil metal interface friction angle and that the rate of the increase was higher in the sandy loam than in the clay loam. The relationship between the draft and the width of the blade could be explained from the observed volume of the soil moved per unit area of the Chisel time face.

From the foregoing, it was clear that the greatest decrease in the draft in the two soils were achieved by the use of the relatively narrow blade of 6.3cm width at a rake of 20 and at a depth of 15.0cm.

4. CONCLUSIONS

The measured failure crescent radius and the observed failure characteristics of the soil during the tillage afforded significant opportunity of appreciating the variations in the draft and tee behaviour of soils to the changes in the geometry of the tillage tool. However, the accuracy in the use of the fie1d failure crescent measurement would depend on the judgment and the skill of the researcher and tool designer in being able to observe and measure the extent of the soil disturbance in a weed coverage field. The experimental errors and the relatively low coefficients of variation indicated that the measurement of the field failure crescent could be quite precise. The measurement of the field failure crescent would also be recommendable because it eliminated the need for unnecessary hydraulic extensions and instrumentations during tillage.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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TABLE 1
ANALYSIS OF VARIANCE ON EFFECTS OF TILLAGE TOOL GEOMETRY ON THE DRAFT FORCE FROM FAILURE CRESCENT MEASUREMENT

Source of variation	Degree freedom	ofSum of Clay Loam	Squares + Sandy Loam	Clay Loam	F. Values Sandy Loam
Total	71	503.24	441.03		
Model	25	453.11	426.19	16.63**	52.84**
Block	2	76.71	6.47	35.19	10.03
Rake Angle (α)	3	20.81	20.18	6.36**	20.85**
Width of Blade (W)	2	217.42	112.97	99.75"	190.58**
α.w	6	14.82	38.17	2.27	19.72*
Dept of tillage (D)	1	78.67	1.65.10	72.18**	511.77**
α .D	3	23.12	13.60	7.07**	14.05**
W.D	2	3.80	19.10	1.74	29.74**
α.W.D	6	17.76	40.50	2.72*	20.92**
Error	46	50.13	14.84		
C V		16.13	11.29		

+ Type IV sum if squares
* Significant at the 5 per cent level
** Significant at the 1 per cent level

TABLE 2

MAIN EFFECTS OF TILLGE TOOL GEOMETRY ON THE DRAFT FORCE (KN) FROM FAILURE CRESCENT MEASUREMENT CLAY LOAM

Level of significance	Unit	Tillage Tool Geometry			
Rake Angle ++					
	Degrees	20	25	30	35
		5.92	5.41	6.53	6.97
0.01		ab	B	a	a
0.05		bc	C	b	a
		Blade Width *			
	cm	6.3	12.7		20.3
		4.08	6.08		8.33
0.01		c	b		a
0.05		c	b		a
		Depth of Tillage **			
	cm	15		25	
		5.12		7.21	
0.01		b		a	
0.05		b		a	

\+ Ducan's new multiple range test.
++ Each value is the mean of 18 observations.
* Each value is the mean of 24 observations.
** Each value is the mean of 36 observations.
In each row, means with the same letter are not significantly different at the level of significance specified.

TABLE 3
MAIN EFFECTS OF TILLGE TOOL GEOMETRY ON THE DRAFT FORCE (KN) FROM FAILURE CRESCENT MEASUREMENT SANDY LOAM

Level of significance	Unit	Tillage Tool Geometry			
Rake Angle ++					
	Degrees	20	25	30	35
		4.35	5.01	4.84	4.92
0.01		c	b	a	b
0.05		c	b	a	b
		Blade Width *			
	cm	6.3	12.7		20.3
		3.38	5.13		6.58
0.01		c	b		a
0.05		c	b		a
		Depth of Tillage **			
	cm	15		25	
		3.52		6.54	
0.01		b		a	
0.05		b		a	

See footnotes in Table 2.

TABLE 4

SUMMARY OF ANALYSIS OF ARIANCE ON THE POLYNOMIAL EGRESSION EQUATION

Soil	Symbol	Units	Polynomial Regression Equation +[++]	Source of Variation	Degrees of Freedom	Sum of Squares	F value	$R1^2.234^2$
				Total	23	419.72		
sandy	P	KN	P = -10.773 + 200.382wd	Regression	5	375.35	30.45**	0.394
Loam			-17.361w + 52 555α	Residual	18	44.34		
Clay	P	KN	P = 5.730 + 121.130wd	Total	23	376.40		
			+6.133w – 20.090α	Regression	.5	346.50	41.72**	0.921
			+25.371α^2	Residual	18	29.90		

** Significant at the one per cent level

+$R1^2.234$ if multiple coefficient of determination of the variation in the dependent variable accounted for by the variation in the rake angle, the width of the blade and the depth of tillage respectively.

++ Rake angle in radians, w is the width of the blade in metres and d is the depth of tillage in metres.

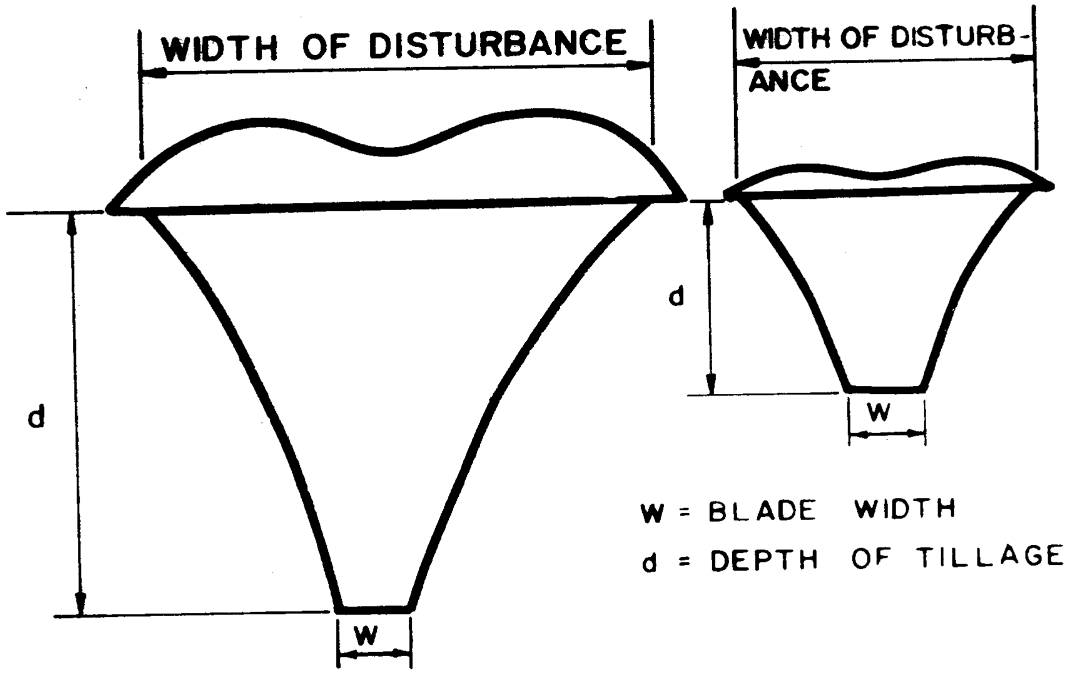

Figure I. Schematic soil failure in two dimensions

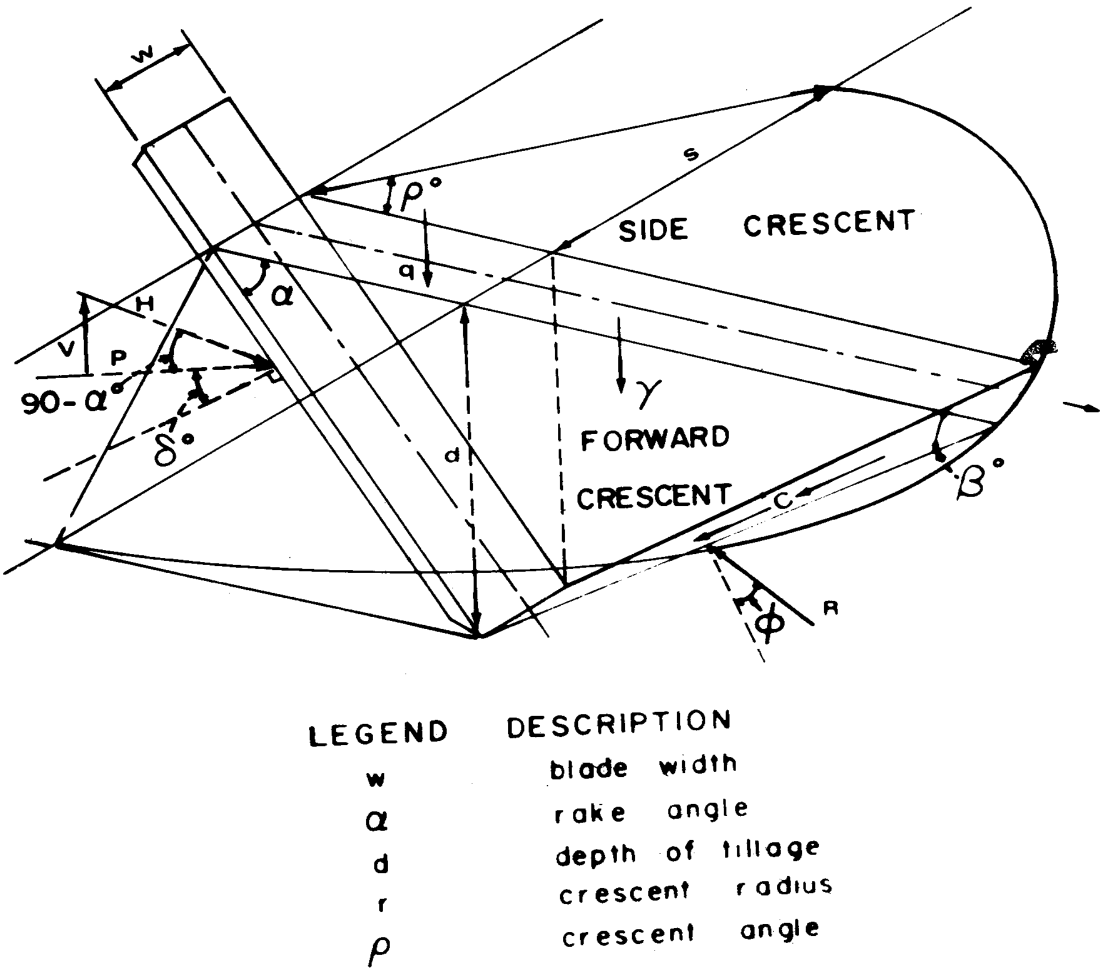

Figure 2: Schematic soil failure in three dimensions

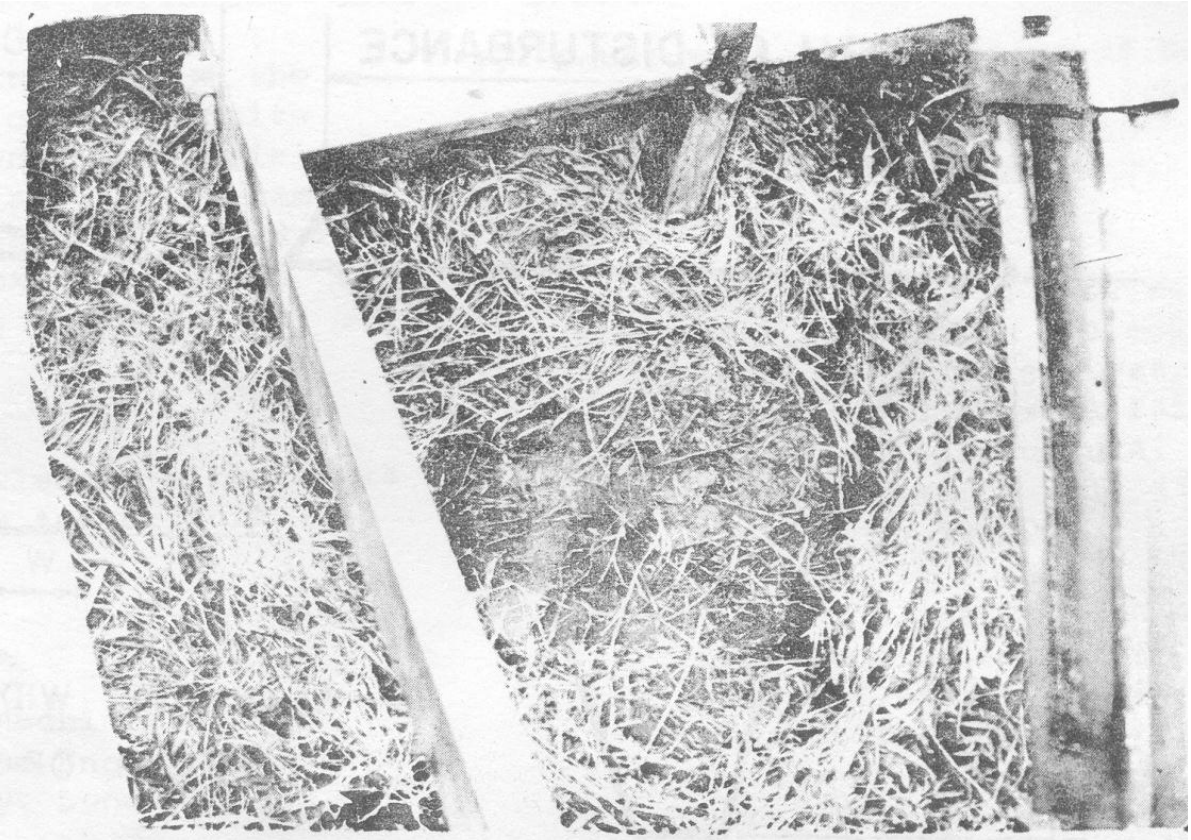

Figure 3: A chisel tine right at the depth tillage

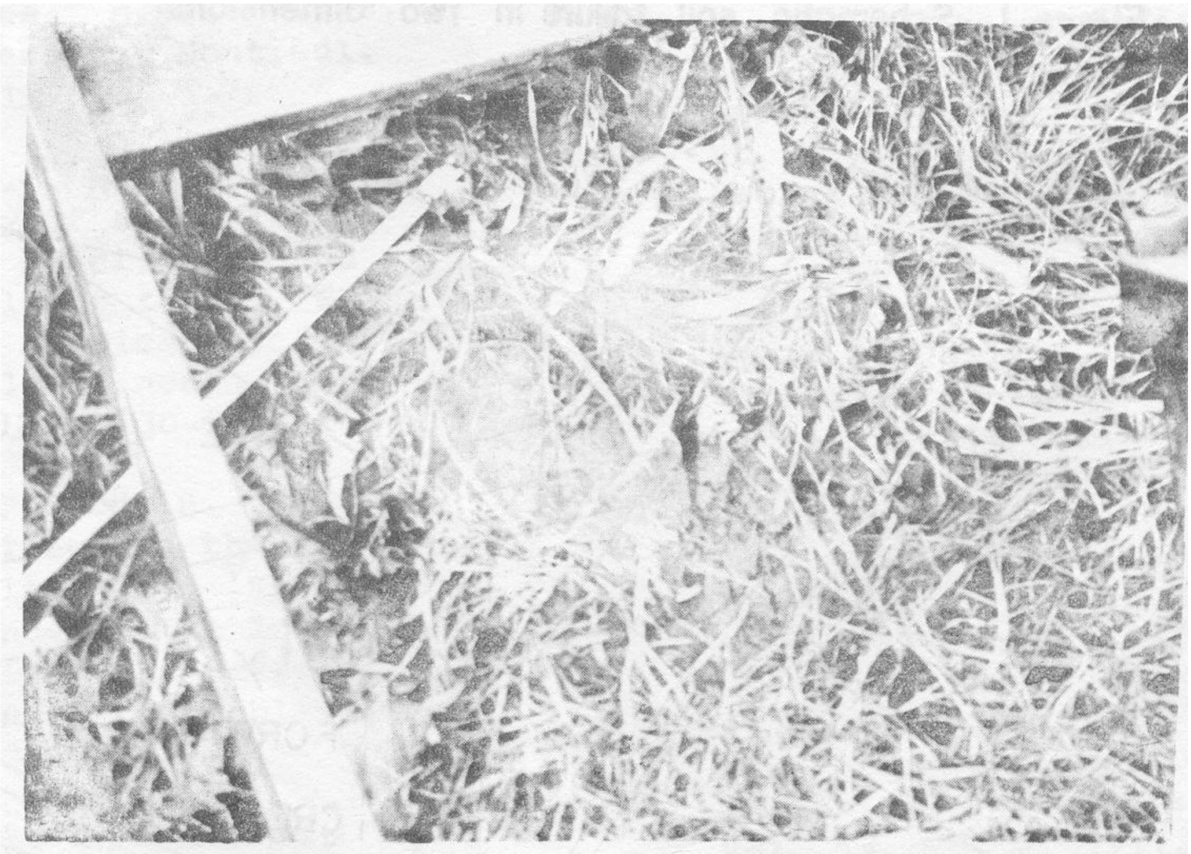

Figure 4: Crack formation and propagation during tillage

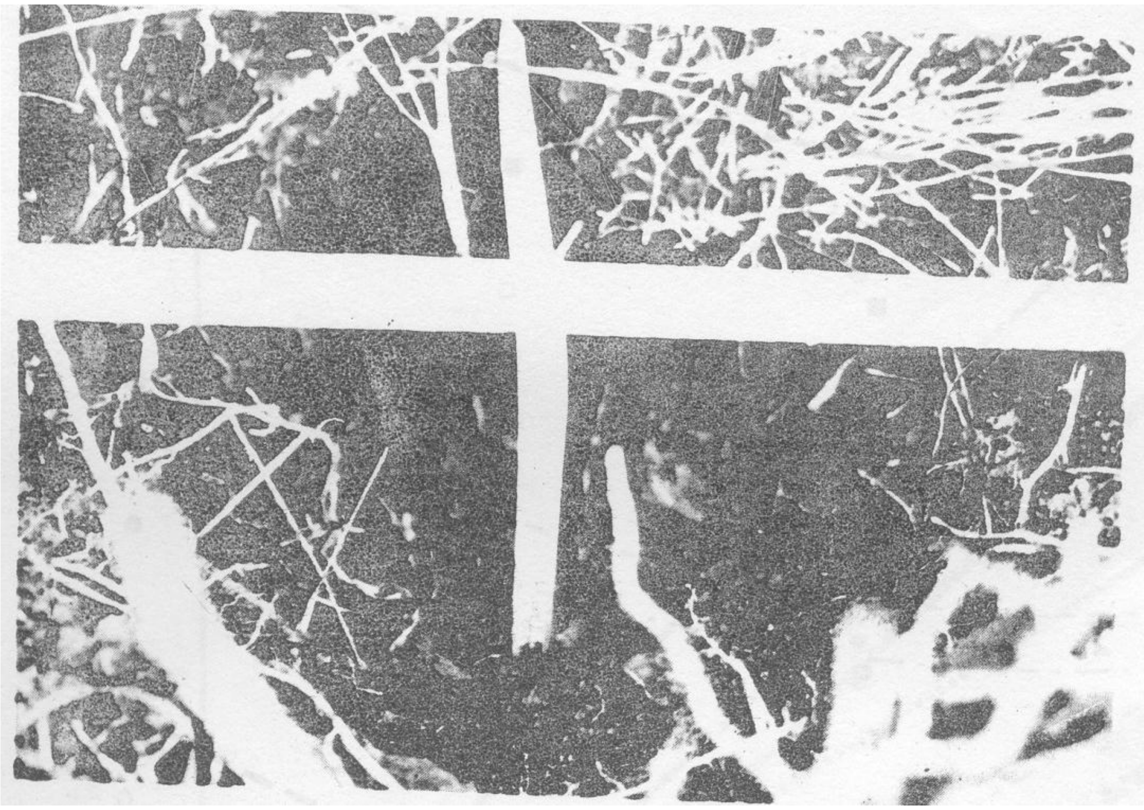

Figure 5. Tillage furrow depth and with measurement

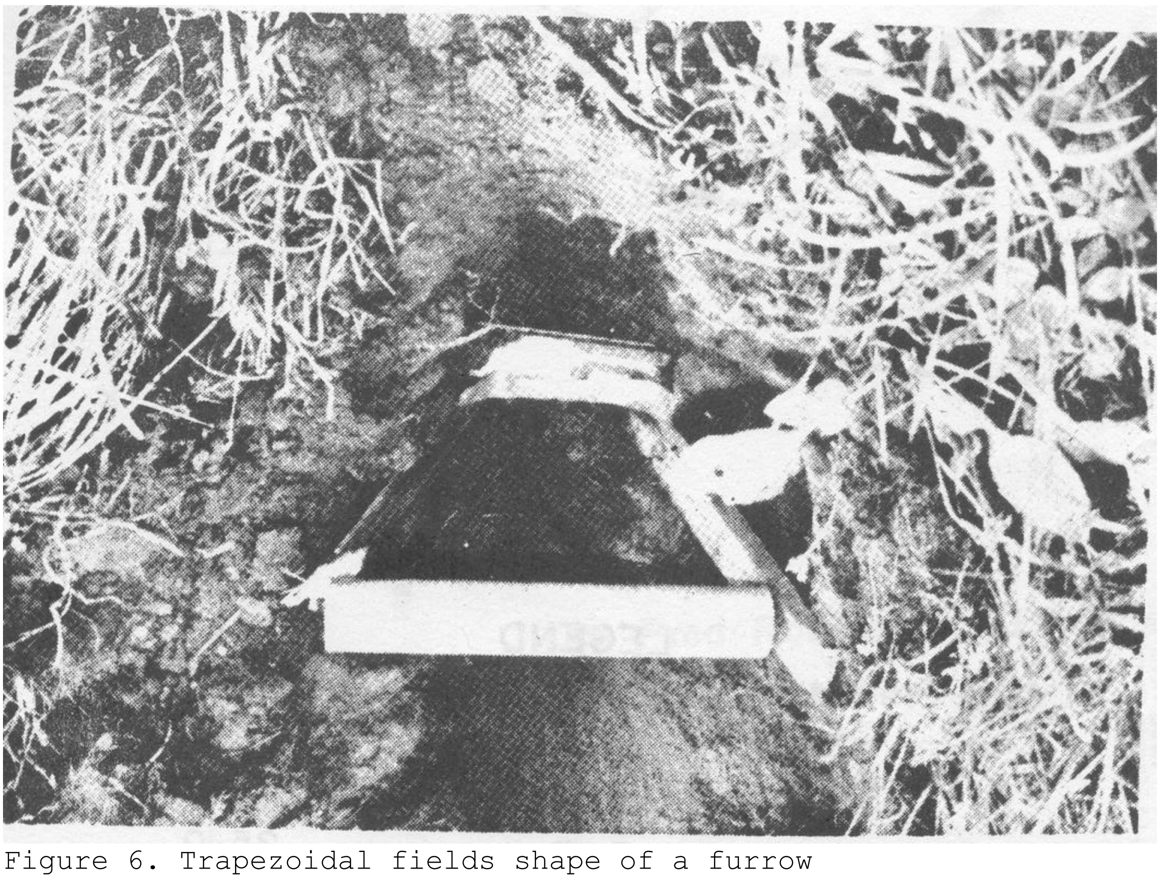

Figure 6. Trapezoidal fields shape of a furrow

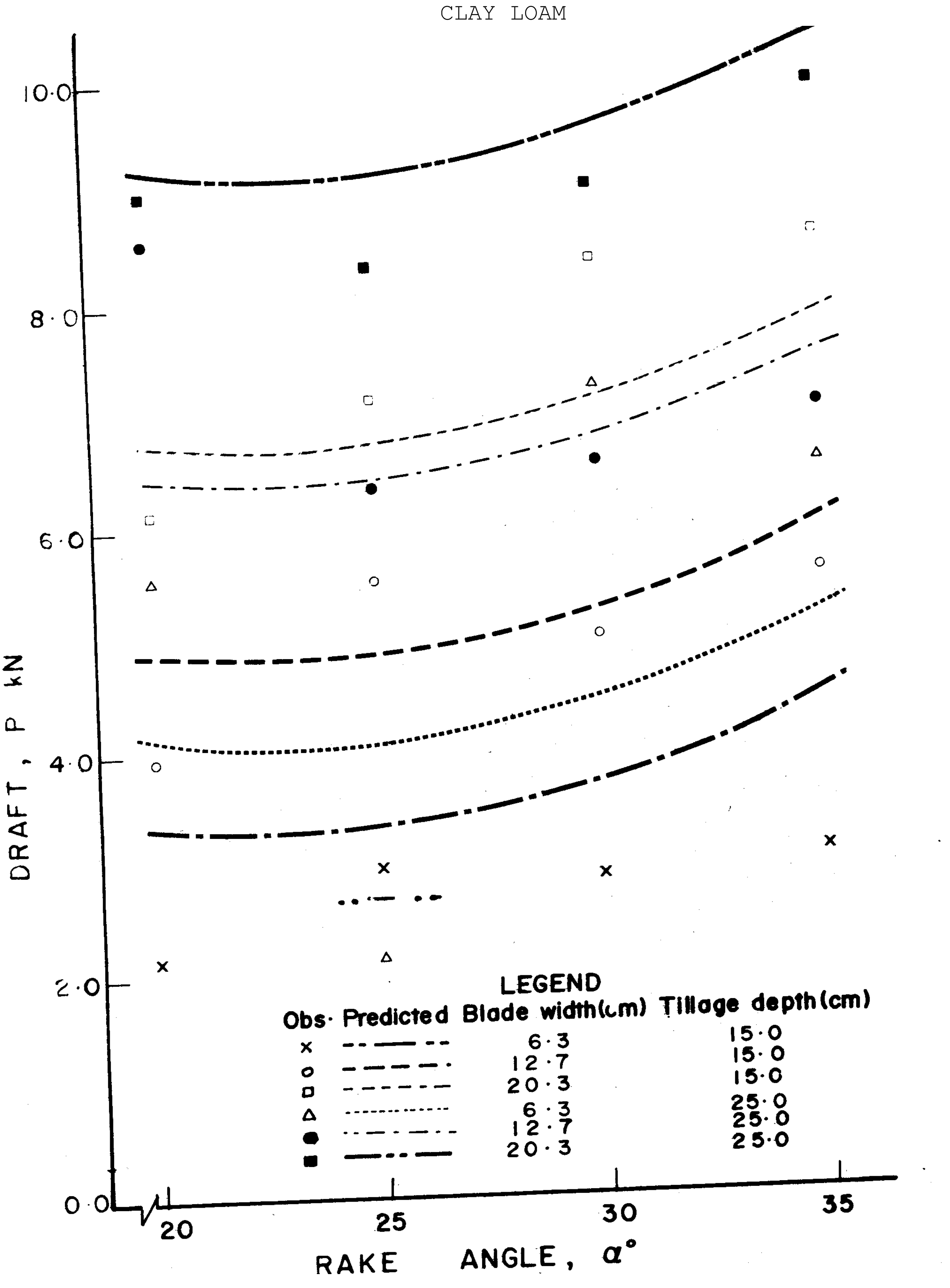

Figure 7. The effect of the rake angle on the draft (NK) calculated from the failure crescent in the clay loam.

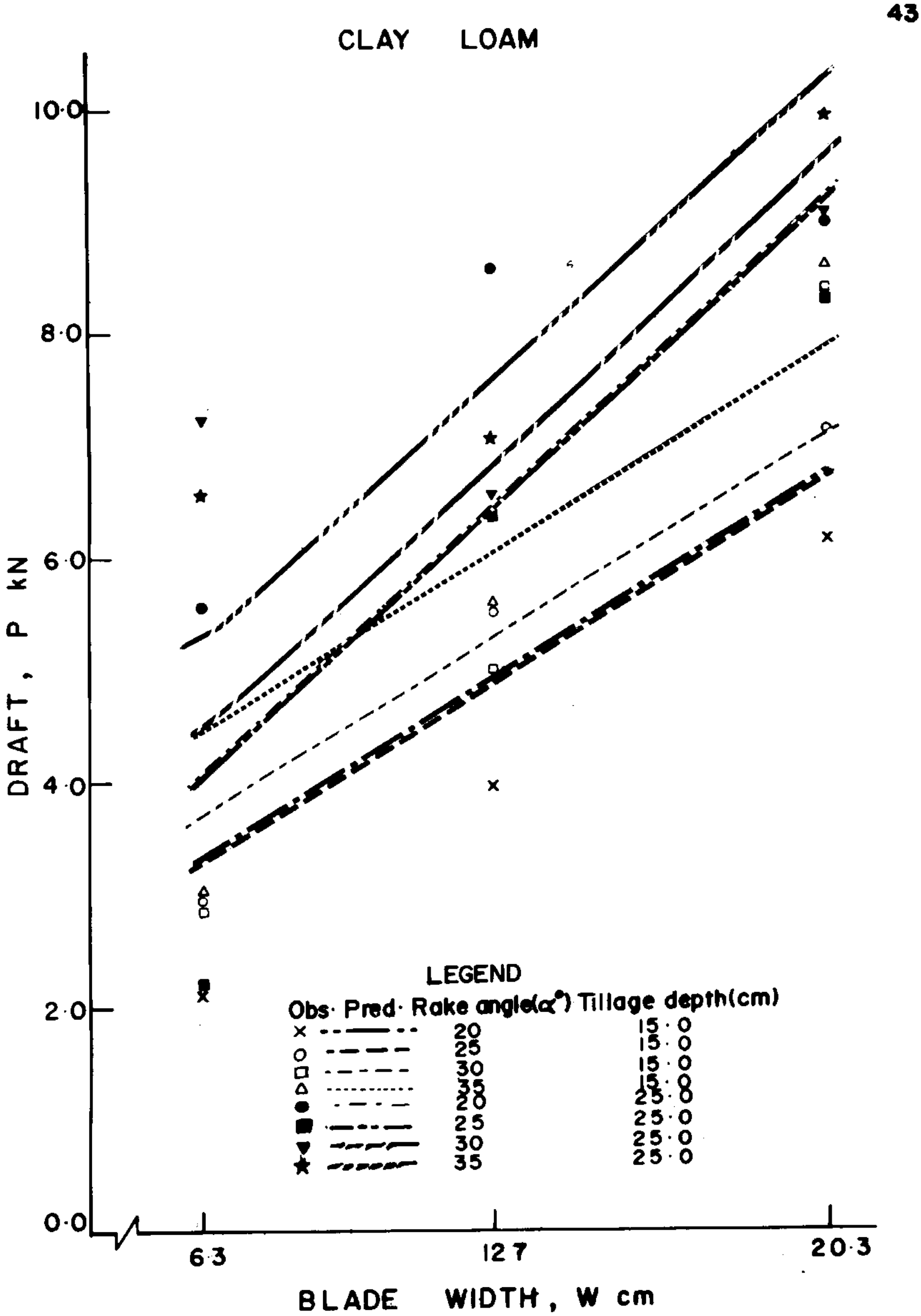

Figure 8· The effect of the blade width on the draft (KN) calculated from the failure crescent in the clay loam.

SANDY LOAM

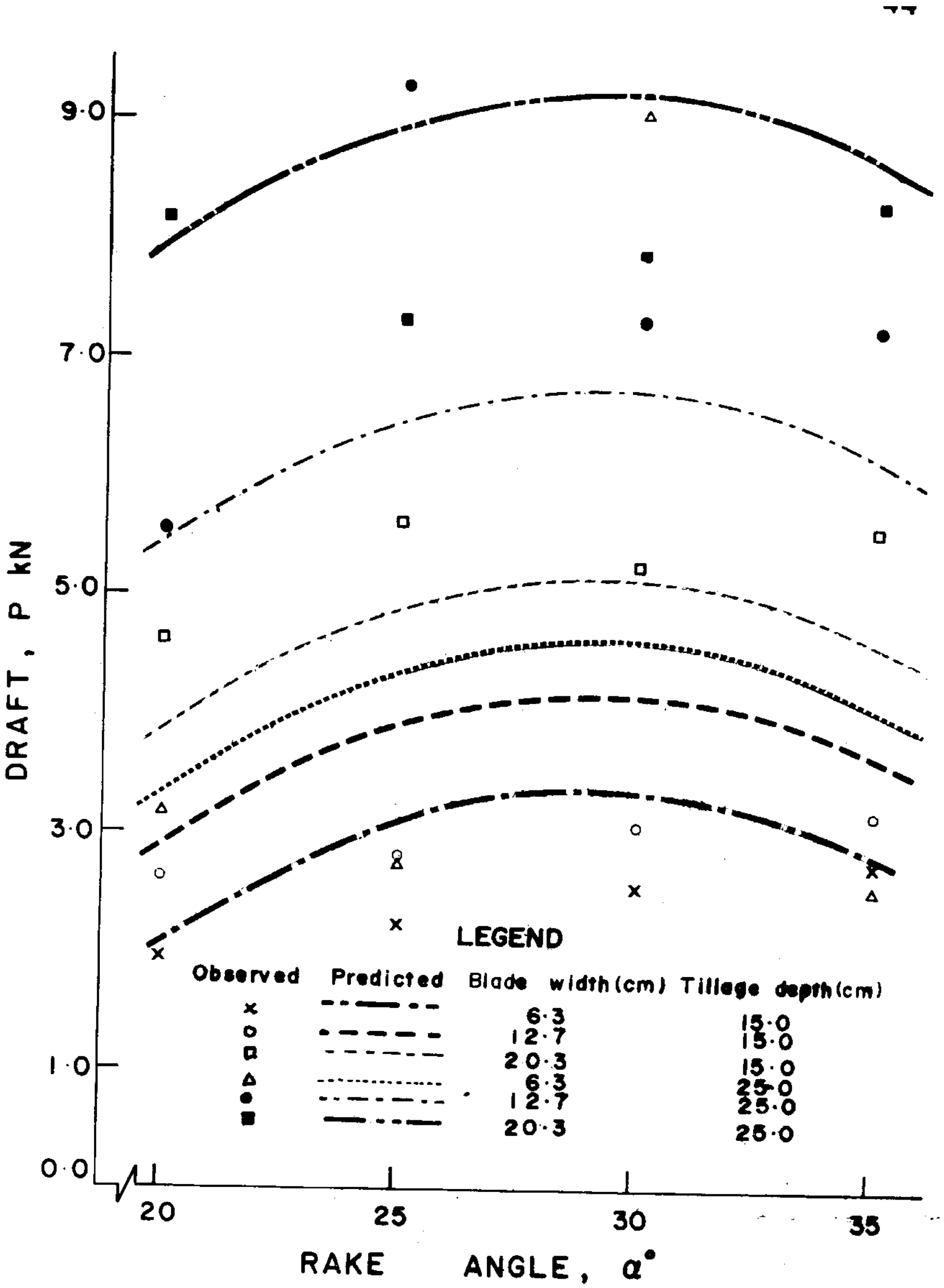

Figure 9 · The effect of rake angle on the draft (KN) calculated from the failure crescent in the sandy loam

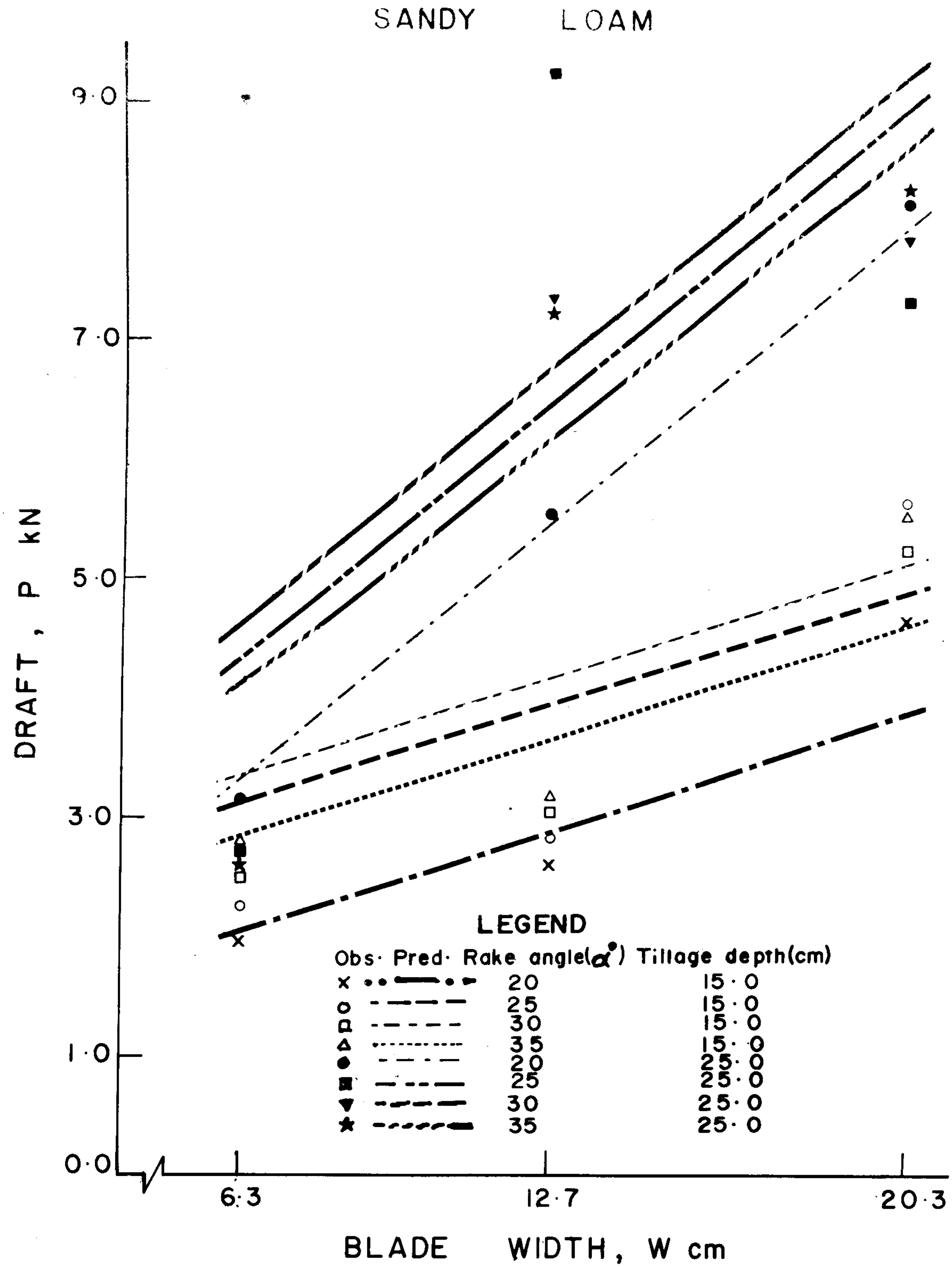

Figure 10. The effect of the blade width on the draft (KN) calculated from the failure crescent in the sandy loam.