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EFFECT OF TILLAGE TOOL GEOMETRY ON SOIL STRUCTURAL STIFFNESS

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Abstract. The concept of structural stiffness signifies the level of resistance a body of agricultural soil develops so as to withstand any form of further deformation from subsequent external loading.

In order to verify the significant effects of tillage tool geometry on the soil structural stiffness, field clay loam and sandy loam soil were tilled with a chisel shaped tine at different tillage geometries. Samples of the tilled soils were sheared in a 'uniform strain' direct shear test box to determine the shear strength parameters from which the structural stiffness was calculated. The effects of the width of the tillage blade, the rake angle, the depth of tillage and their interactions on the clay loam and the sandy loam structural stiffnesses were significant at the 5 % level or higher. From this study, it was possible to predict from the structural stiffness concept the shear resistance behaviour of a soil that has been tilled with a tillage tool of known geometry.

Keywords: tool geometry, soil stiffness and behaviour

INTRODUCTION

With the current intensive cultivation of soils in many parts of the world, and the use of large powerful machinery on agricultural soils, traction, compaction and erosion problems have become of great concern in agriculture. All soil cutting, tillage and moving tools transfer soil from one location to another. The soil materials fail mechanically in the process in the sense that the mass of soil being moved does not retain its original position and structural shape. The extent of the dislocation and distortion of the soil mass depends on the shear characteristics of the soil. The extent of resistance to the above mentioned changes depends on the soil developed structural stiffness and the geometry of the tool. For example, it was recognized some time ago by Zelenin [15] and Kostritsyn [8] that a very narrow soil cutting tool might not be able to lift soil up over its entire depth under certain conditions. There is, thus, a critical depth, below which a soil is not lifted toward the soil surface, but rather is compressed to the sides of the tool and is moved in a horizontal plane [9]. It is evident from this illustration that there is a relationship between the tillage tool geometry and the soil behaviour during tillage.

In order to look at these problems from tillage tool design considerations, one has to examine tilled soil behaviour in response to the machinery loads applied in field work. Thus, a thorough knowledge of the reactions of the soil to the movement of the tillage tool and of the changes in properties of the tilled soil is required to develop the relevant desing principles in soil tillage tool mechanics. Some previous studies have for example reported on the effects of tillage tool geometries on the volumetric changes that occur on already tilled soils [6,7]. Unfortunately, the knowledge of the shear behaviour or reaction of tilled soil to external forces which initiate shear and compaction in the tilled soil has remained limited. Though considerable knowledge exists on stress and strain behaviour of soils, such knowledge is only useful so long as the soils remain as continuous bodies [9]. However, this knowledge is yet to be extended to tilled agricultural soils that have been fragmented or fractured with fissures. It is therefore necessary that the stress and strain behaviour of tilled agricultural soils be quantified in accordance with the manner the soils relate to the external forces from farm machinery traffic or other secondary tillage activities in the field. In a study to develop this relationship, Ijioma [5] established the concept of soil structural stiffness which relates the resistance of an agricultural soil to the distortion and deformation forces that act on soils. This stiffness concept has been proved to rightly quantify the behaviour of tilled soils [5].

It is therefore reasonable to find out how the design changes in a tillage blade affect the structural stiffness of tilled agricultural soils.

The mechanical design changes in an earthmoving or tillage blade of interest in this study include the width of the blade, the rake angle or angle of approach of the blade into the soil and depth of tillage in the soil. These three design features reflect the tillage tool geometry. The objective of this study is therefore to determine statistically if a tillage tool geometry has significant effect on the structural stiffness of a tilled agricultural soil.

THEORETICAL BACKGROUND

Studies by Yong and McKyes [14] have shown that the concept of octahedral stiffness represents a measure of engineering soil material behaviour. The octahedral stiffness is a function of soil density and average stress level. It varies with the physical changes that occur in particle connections and indirect forces as the soil fabric is altered by shearing movements. The octahedral stiffness concept, is therefore a relationship between the octahedral shear strain and stress increments of a soil sample in compression and shear. This concept has been modified further to describe the structural stiffness of a tilled agricultural soil [5].

The octahedral stiffness is thus derived from the following relationship established by Hill [3]:

$$d\varepsilon_x/\sigma'_x = d\varepsilon_y/\sigma'_y = d\varepsilon_z/\sigma'_z = d\gamma_{xy}/\tau_{xy} = d\gamma_{yz}/\tau_{yz} = d\gamma_{zx}/\tau_{zx} \tag{1}$$

where $d\varepsilon_x$, $d\varepsilon_y$ and $d\varepsilon_z$ are principal strain increments in x, y and z directions, σ'_x, σ'_y and σ'_z are effective principal stresses in x, y and z directions; τ_{xy}, τ_{yz} and τ_{zx} are shear stresses in the directions indicated; $d\gamma_{xy}$, $d\gamma_{yz}$ and $d\gamma_{zx}$ are incremental shear strains in the directions indicated.

Assuming the soil to be a compact work hardening material, Eq. (1) takes the forms:

$$d\varepsilon_{ij} = \sigma'_{ij}\, d\lambda_s \tag{2}$$

$$d\lambda_{ij} = \tau_{ij} d\alpha_s \tag{3}$$

where λ is a function of the instantaneous structure of aggregate contacts at slip or deviation angle while $d\lambda_s$ is a scalar factor of proportionality; λ_s is not a material constant but varies during deformation.

On an octahedral plane, the shear stress and strain parameters in Eqs (1) and (3) can be generalised to:

$$\tau_{oct.} = d\gamma_{oct.}/d\lambda_s \tag{4}$$

$$d\varepsilon_i = \sigma'_i\, d\gamma_{oct.}/\tau_{oct.} \tag{5}$$

$$d\varepsilon_{ij} = \sigma'_{ij}\, d\gamma_{oct.}/\tau_{oct.} \tag{6}$$

where $\tau_{oct.}$ is the octahedral shear stress in the octahedral plane while $d\gamma_{oct.}$ is the incremental shear strain in the octahedral plane.

Rearranging Eq. (6) above:

$$\tau_{oct.}/d\gamma_{oct.} = \sigma'_{ij}/d\varepsilon_{ij} \tag{7}$$

Equation (7) above represents the concept of octahedral stiffness as defined by Yong and McKyes [14] for engineering materials in continuum. Redefining the stiffness behaviour of a friable agricultural soil in the three phase state of a structure containing voids and solids, an assumption is hereby made that as the soil is deformed, very small elastic strains occur with the increments of stresses. With this assumption, Eq. (7) is thus modified for purposes of establishing the appropriate soil tillage mechanics equation applicable to the shear stress-strain behaviour of agricultural soils. The modified equation takes the form:

$$H = d\tau_{oct.}/d\gamma_{oct.} \qquad (8)$$

where H is the structural stiffness, a relative concept, which characterizes the resistance of the soil structure to deformation and distortion forces. The deformation and distortion processes in a tilled friable agricultural soil depend on the various loosening and compacting processes to which the seedbed has been subjected during cultivation. Thus this stiffness concept also quantifies the resistance of the soil to subsequent deformation, root penetration and the like, and therefore is a measure of mechanical behaviour.

These use of strain increments is dictated by the consideration that the amount of work hardening is not only determined by the difference between the initial and final shapes of an element but also by the summation over the whole strain path that denotes the stress-strain history of the soil material.

The stress-strain characteristics of such a soil can be determined from a strain controlled test on the tilled soil. However, in this paper it is assumed that, when plotted, the stress-strain data of strain controlled shear tests show increments of stress at the same strain for different normal loads (Figs 1,2). The theoretical combination of the curves in Fig. 2 produce a curve which approximates to a stress controlled test for a small soil sample in a shear device.

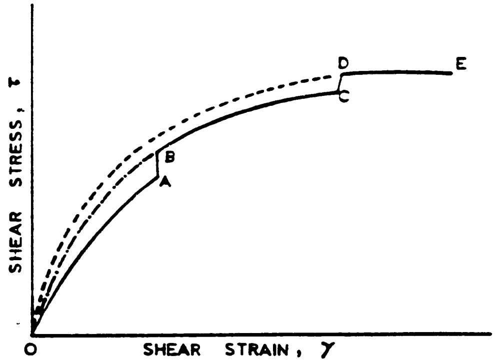

Fig. 2. Stress strain curves from strain-controlled tests theoretically combined in the failure zone to resemble stress-controlled test.

METHODS AND MATERIALS

Tillage blades of 6.3, 12.7 and 20.3 cm widths were used at rake angles of 20, 25, 30, and 35° to loosen clay loam and sandy loam field soils at depths of 15.0 and 25.0 cm. The design and construction of such tillage tools have been described by Ijioma [5].

The random combination of the tillage tool geometries produced a total of 24 treatment combinations of blade width, rake angle and depth of tillage. The tillage implements were constructed in the Department of Agricultural Engineering of McGill University, Montreal, Canada.

The field experiments which consisted mainly of soil tillage and soil shear tests were

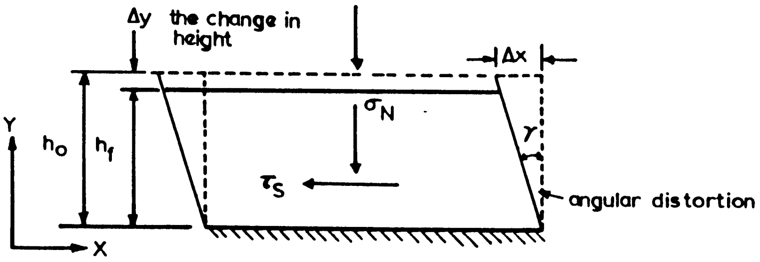

Fig. 1. Simple uniform shear strain device.

carried out in two different fields. One field was of clay loam soil while the other was of sandy loam soil. Each experimental field measuring 62.5 m x 39 m was laid out parallel to the direction of the slope of the field surface. The field treatment plot in a block was 9 m long by 2.5 m wide. In each field of three blocks, a turn strip of 3 m wide by 62.5 m long was marked out at both ends of each block to enable the tractor and the trailer to turn safely from one experimental plot into another. The 24 treatment combinations corresponded to the 24 treatment plots in a block. In addition to the 24 treatment plots in a block, a zero tillage control plot was added to make up 25 treatment combination plots in the block. Each soil type therefore had a total of 75 treatment plots which summed up to 150 plots for the two soil types studied.

The three blocks in each field corresponded to three soil moisture content ranges which resulted from natural precipitation and the periodic spacing of the experiments (Table 1). The moisture content range in each block was based on the preliminary values of the field soil consistency limits. The consistency limits were determined on soil samples that were obtained from three equally spaced out locations

Table 1. Structural stiffness (H) and water content (WC) of clay loam and sandy loam

Plot No.	Treatment combination of tillage tool geometry			Clay loam		Sandy loam	
	α	W	D	H	WC (%)	H	WC (%)
1	1	1	1	39.15	26.88	38.04	19.12
2	2	1	1	41.17	27.27	37.20	17.45
3	3	1	1	51.34	27.24	36.65	16.93
4	4	1	1	42.46	28.42	36.93	18.46
5		2	1	47.67	27.28	51.89	18.70
6	2	2	1	42.42	26.22	40.82	18.55
7	3	2	1	35.34	28.67	41.56	18.88
8	4	2	1	40.66	25.01	41,46	17.52
9	1	3	1	33.44	23.82	44.83	18.85
10	2	3	1	28.60	27.48	41.48	19.34
11	3	3	1	43.42	28.98	48.68	17.07
12	4	3	1	33.93	26.10	39.33	19.43
13	1	1	2	54.05	24.88	29.49	18.62
14	2	1	2	37.73	28.13	27.84	18.84
15	3	1	2	48.39	29.01	23.77	15.17
16	4	1	2	38.85	26.65	24.81	16.91
17	1	2	2	31.26	25.15	36.15	16.35
18	2	2	2	44.22	24.86	29.45	20.40
19	3	2	2	44.90	25.95	27.77	18.28
20	4	2	2	27.37	25.18	28.46	19.00
21	1	3	2	36.06	28.57	48.01	19.22
22	2	3	2	31.70	28.04	37.40	18.45
23	3	3	2	44.22	26.93	30.26	18.09
24	4	3	2	33.52	24.79	27.54	18.13
25	0	0	0	45.28	29.41	44.71	29.67

		1	2	3	4
α	Rake angle (deg)	20°	25°	30°	35°
W	Width of blade (cm)	6.3	12.7	20.3	
D	Dept of tillage (cm)	15.0	25.0		
WC	Water content (%)				
H	Structural stiffness (kPa)				

in each field. The soil plastic limit, plasticity index and the optimum moisture content from the moisture-density relations tests were the basic criteria used in the dividing and laying out each field into three different blocks.

The experimental fields had been left fallow and uncultivated for the three years preceding the experiments. The soils in these fields were not significantly disturbed, having been mown, marked out and left undisturbed for a month prior to testing. The fields were located in the Macdonald Campus of McGill University in Ste Anne de Bellevue, Quebec, Canada.

The tillage operation was done on each marked plot using the corresponding blade of a certain width and rake angle and at the depth of tillage indicated in the plot lay-out. Direct shear tests were performed near the field plots, so as to avoid soil disturbance during transportation. The loosened soil samples were cored at 100 mm above the bottom of the furrow whereas the soil in the control treatment plot was cored at a depth of 50 mm from the soil surface. These depths were chosen to minimize the soil disturbance and to closely represent the depth specifications for the treatment combinations. The shear box which was used for the tests was the uniform strain direct shear box similar to the types described by Raghavan and McKyes [11] and Roscoe [12]. The disturbance of the soil during core sampling and handling from the furrow to the shear box stand was minimized by the use of a core sampler developed for soil particulate studies [4].

Three sets of direct shear tests were done for the normal loads of 9.81, 19.61 and 49.03 N on the soil samples from each treatment plot. The stress and the corresponding strain readings were used to calculate the structural stiffness of the soil as in Eq. (8) above.

From the three sets of the applied loads in the vertical direction in the shear box, the corresponding normal stresses were 0.92, 1.85 and 4.62 kPa. Correspondingly, the change in the normal strains $d\varepsilon_{y1}$, $d\varepsilon_{y2}$ and $d\varepsilon_{y3}$ were calculated by respectively subtracting the initial normal strain in each test from the final normal strain. Similarly, the corresponding shear strain increments were obtained from the initial and final shear strains. The stresses and strain increments were analyzed following the Mohr's circle diagrams for stress and strain increments.

In each soil sample from a treatment combination plot, the structural stiffness developed during shear was calculated from:

$$H = (\tau_{oct.\,3} - \tau_{oct.\,1})/d\gamma_{oct.\,3} \qquad (9)$$

Polynomial regression equations were established to relate the tillage tool geometry to the structural stiffness. The regression equations were therefore used to predict the structural stiffness that resulted from the use of a tillage tool of a specified blade width, rake angle and depth of tillage. The predicted structural stiffnesses were used to curve fit the graphs of rake angle and blade widths against the experimentally determined structural stiffnesses (Figs 3-6).

RESULTS AND DISCUSSION

Table 2 shows the statistical levels of significance of the effects of the tillage tool geometry and their interactions on the structural stiffness of the tilled clay loam and the tilled sandy loam.

In Fig. 3, the line drawings show graphical relationships between the tillage tool geometry and the observed structural stiffnesses. The structural stiffnesses in the tilled clay loam and sandy loam soils were relatively lower than the structural stiffnesses in the untilled soils. These differences confirm the fact that soil tillage which is a form of soil disturbance generally affects soil behaviour. However, in establishing a clear relationship between the tillage tool geometry and the soil structural stiffness, polynomial regression equations were statistically tested on the experimental data. The following polynomial regression equations showed some level of statistical significance on the relationship between the structural stiffness, H, and the various tillage tool geometries.

The polynomial regression equations relating the tillage tool geometry to the predicted structural stiffness are:

Table 2. Summary of analysis of variance on the effects of tillage tool geometry on soil structural stiffness [H, kPa]

Source of variation	Degrees of freedom	Sum of squares+		F values	
		clay loam	sandy loam	clay loam	sandy loam
Total	74	7085.79	6275.28		
Model	26	4424.51	4638.48	3.07**	5.23**
Bloc	2	917.08	161.71	8.27	2.37
C Versus α WD Combination^{++}	1	90.92	106.67	1.64	6.06
Rake angle (α)	3	743.76	701.75	4.47**	6.86*
Blade width (W)	2	880.54	701.78	7.94**	11.32**
$\alpha \cdot W$	6	571.69	225.10	1.72	1.10
Depth of tillage (D)	1	6.79	2045.08	0.12	59.97**
$\alpha \cdot D$	3	172.18	182.90	1.04	1.79
$W \cdot D$	2	142.42	97.30	1.28	1.43
$\alpha \cdot W \cdot D$	6	899.14	246.19	2.70*	1.20
Experimental error	48	2261.28	1636.80		
Coefficient variation %		18.67	15.96		

+ Type four sum of squares; ++ α WD represents the treatment combination of the rake angle (α), the blade width (W) and the depth of tillage (D). C is control treatment which is zero tillage in this study; * Significant at the 5% level; ** Significant at the 1 % level.

$$H = 8.31 - 32.17WD - 54.10W + 177.63\alpha - 191.56\alpha^2 \qquad (10)$$

for the clay loam. For the sandy soil, the relationships are:

$$H = 72.35 - 646.95WD + 1184.73W - 156.38\alpha - 132.00\alpha^2 \qquad (11)$$

In the above equations H is structural stiffness, W is blade width, D is depth of tillage and α is blade rake angle. These equations were statistically the best fit for the experimental results. H is in kPa, the rake angle is in radians, the blade width and the depth of tillage are in metres.

In Fig. 4, the structural stiffness, H, of the tilled clay 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 the tillage. Above that point, the structural stiffness, H, of the tilled clay loam decreased curvilinearly with the increase in the rake angle of that tillage blade. In Fig. 5, the structural stiffness, H, of the tilled clay loam decreased with the increase in the width of the tillage blade of certain rake angle and at a certain depth of the tillage. In the clay loam which was tilled with a tillage blade of a certain width and rake angle, the structural stiffness, H, decreased with the increase in the depth of the tillage (Figs 4 and 5).

In Fig. 6 the structural stiffness of the tilled sandy loam decreased curvilinearly with the increase in the rake angle of a tillage blade. In Fig. 7 the structural stiffness of the tilled sandy loam increased with the increase in the width of the tillage blade of a certain rake angle and at a certain depth of tillage. In the sandy loam which was tilled with a tillage blade of a certain width and rake angle, the structural stiffness decreased with the increase in the depth of the tillage (Figs 6 and 7).

In the clay loam which was tilled with a tillage blade of 20.3 cm at any rake angle and depth of tillage, the structural stiffness was lower than that of the untilled soil. In the sandy loam which was tilled with a tillage blade of 6.3 cm at any rake angle and depth of tillage, the structural stiffness was lower than that of the untilled soil.

The statistical analysis and the graphical relationships show that the structural stiffness vary in accordance with the soil initial preconditioning and due to the initial applied stresses

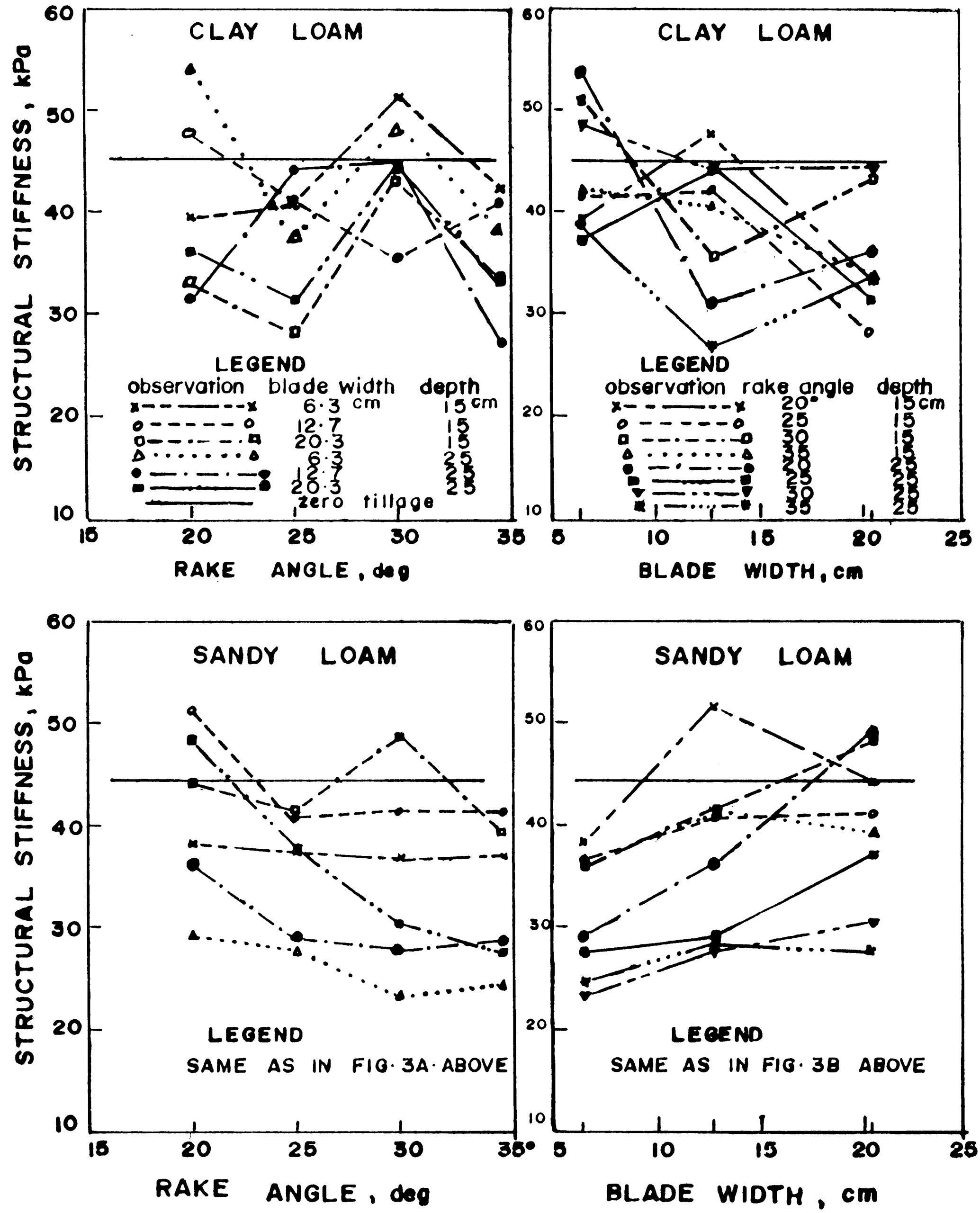

Fig. 3. Line diagrams showing the effects of tillage tool geometry on structural stiffness in clay loam and sandy loam soils.

prior to the shearing of the soil. These results seemed to be substantiated by the findings on other soil related studies in the literature. Yong and McKyes [14] observed that the stiffness of a soil structure was a function of the density and the average stress level and that its variation would result from the physical changes occurring in the particle connections and indirect

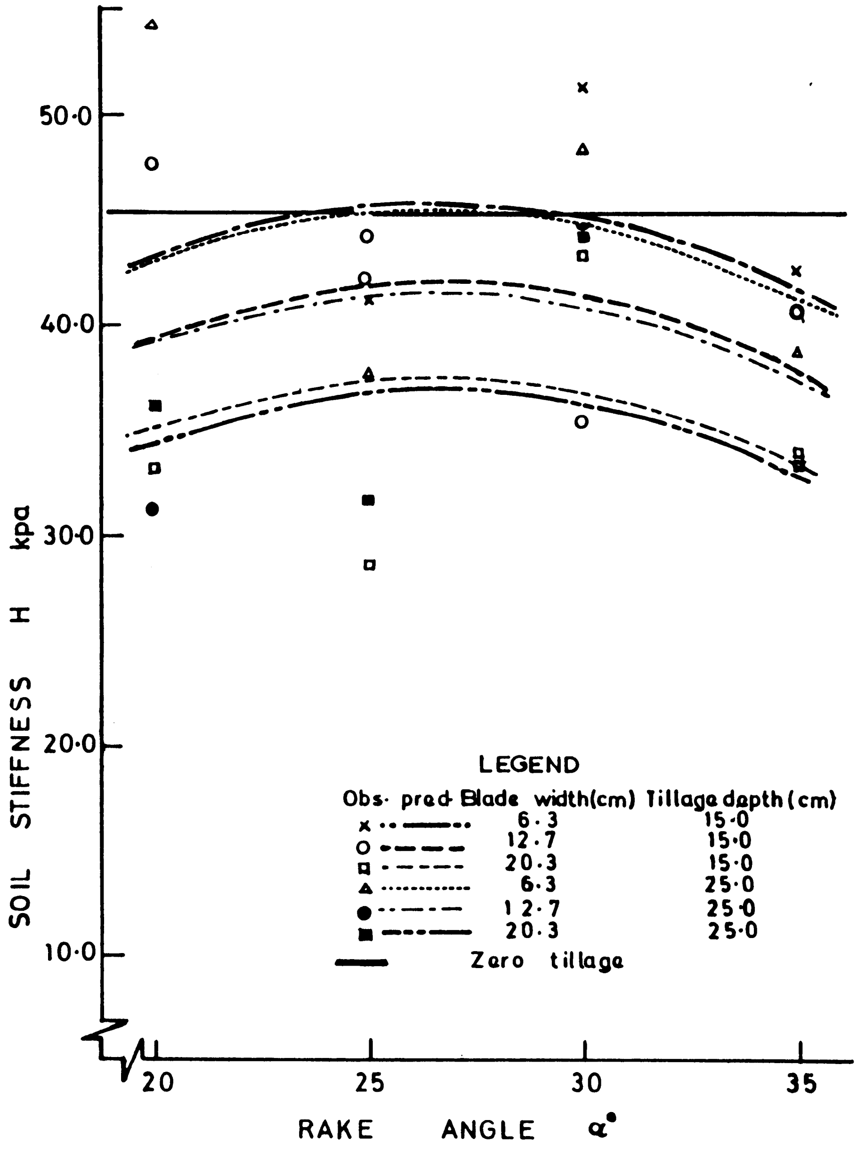

Fig. 4. The effect of tillage by tools of different rake angles on the structural stiffness in the clay loam.

forces as the soil fabric was altered by shearing movements. Equation (8) in the theoretical background and the experimental procedure used in deriving the structural stiffness point to a possible correlation between the structural stiffness and the soil shear strength parameters. It therefore becomes reasonable to draw similar inferences in the effects of soil moisture and density on the structural stiffness as exist in the effects of soil moisture and density on the soil shear strength parameters. Such similar relations have been reported by Ijioma [5,7].

The practical significance of the structural stiffness could be illustrated from some of the tilled soil whose structural stiffnesses were equal to or higher than those of the untilled soils.

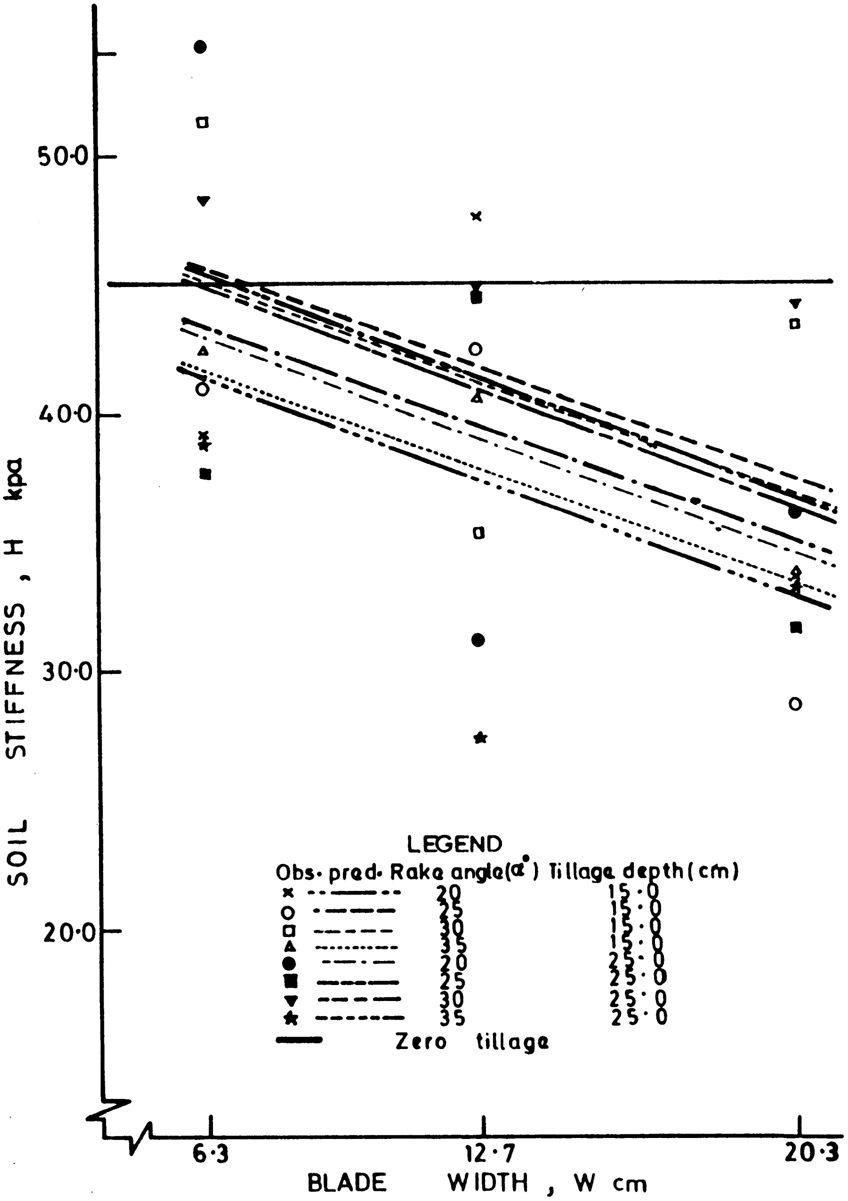

Fig. 5. The effect of the blade width on the structural stiffness in the clay loam.

These soil behaviours could be explained from other studies on soil behaviour during and after tillage. Cooper [1] suggested that care should be taken not to run over tilled soil with heavy loads because soil which was broken up and recompacted was often more dense than it was before tillage. Hettiaratchi and Ferguson [2] observed that the stresses developed by a soil medium against a plant root produced a mechanical impedance or constraint in the growth process of the root. They suggested that the mechanical impedance to the root growth depended not only on the various loosening and compacting processes to which the seedbed had been

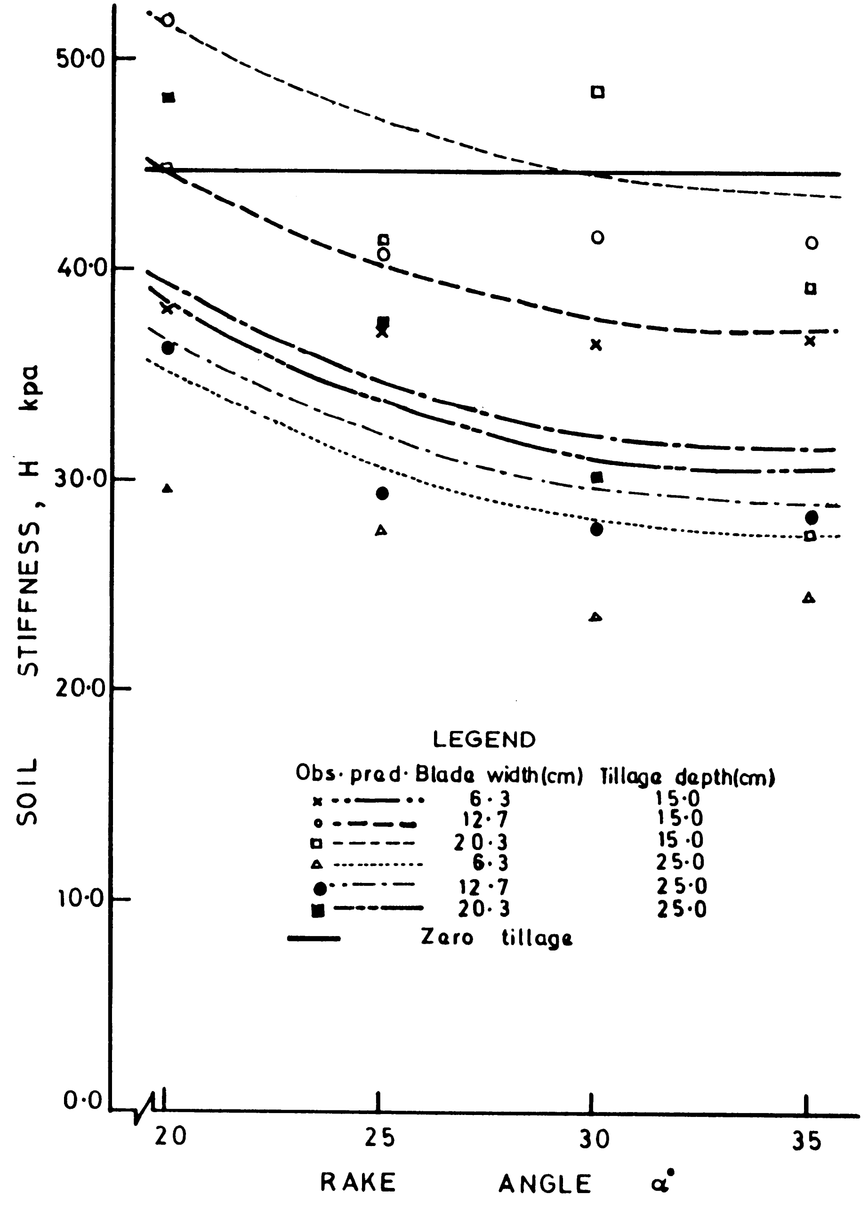

Fig. 6. The effect of the rake angle on the structural stiffness in the sandy loam.

subjected during cultivation but also on the type, composition and the condition of the soil.

From the foregoing, it was evident that the tendency of the tilled soil to resist any form of deformation could also be explained by the concept of the structural stiffness. This has been substantiated by the statistical significance of the effect of the tillage tool geometry on the structural stiffness. From the graphical relationships, it was clear that any desire to achieve a tilled soil of a structural stiffness lower than that of the untilled soil requires the proper selection of the tillage tool geometry. Such a desire could arise when a seedbed

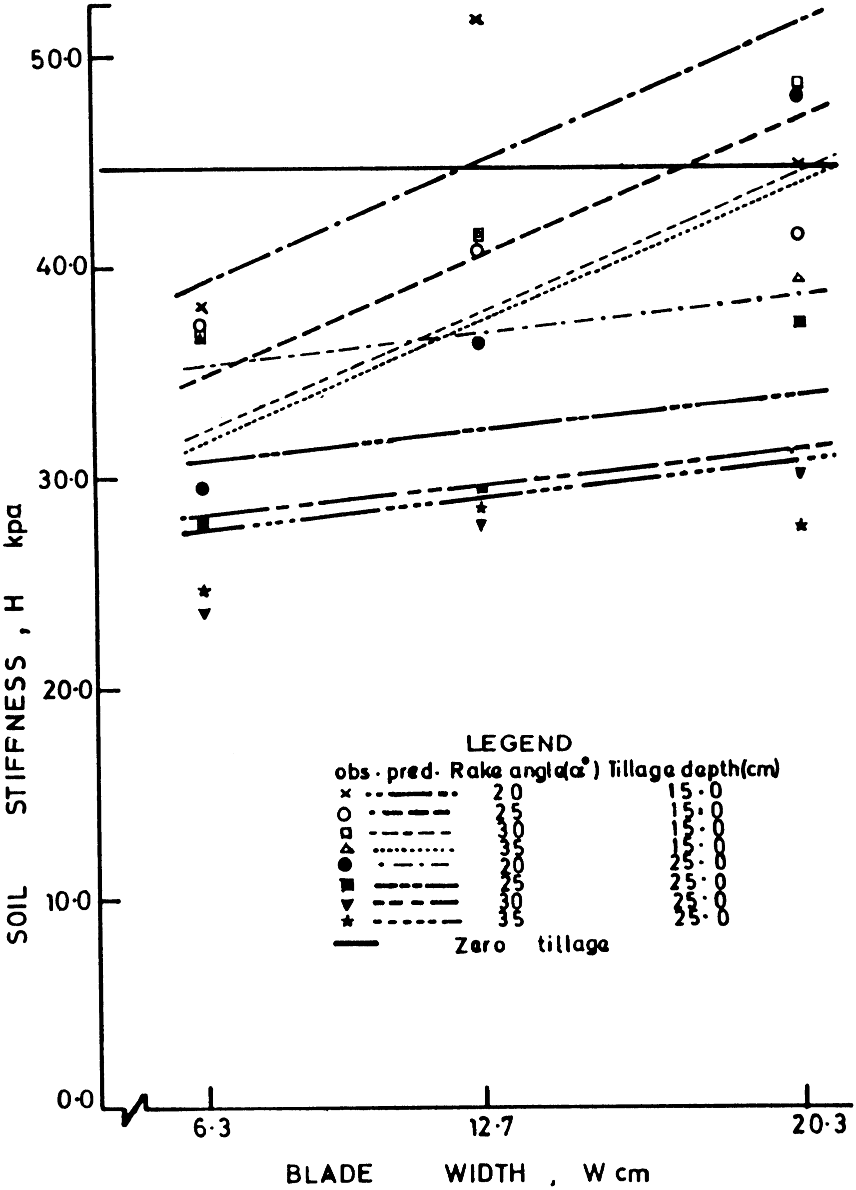

Fig. 7. The effect of the blade width on the structural stiffness in the sandy loam.

should be prepared so as to minimize soil resistance to plant rooting and root propagation.

CONCLUSION

The results of the experiments and the analysis demonstrate the sensitivity of the structural stiffness to the effect of the tillage tool geometry. In agreement with the findings of Schofield and Wroth [13] it was apparent that engineering design calculations should consider not only the yield strength of the soil material but also the structural stiffness of the soil structure. It was evident that as additional analytical tools are provided to implement designers, so the structural stiffness of the soil becomes a subject of increasing interest and importance to geotechnical engineers, farmers and agricultural tillage tool designers.

ACKNOWLEDGEMENT

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