Subsoiling forces and tool speed in compact soils

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Owen, G. T. 1989. **Subsoiling forces and tool speed in compact soils.** Can. Agric. Eng. **31**: 15-20. The effect of tool speed on the forces and soil disturbance associated with subsoiling was investigated in a compact clay loam and a compact sandy loam under field conditions. Regression analyses revealed that tool speed had a highly significant linear effect on the vertical force, and had a highly significant quadratic effect on the horizontal force, total force, moment and specific resistance. In all cases, however, the contribution of tool speed or tool speed squared was small. Soil type also had a highly significant effect on the forces, the moment and the specific resistance. No interactions between soil and tool speed or between soil and tool speed squared were observed. Neither soil nor tool speed had a significant effect on the soil areas heaved or disturbed, the total area, the width of disturbance or the swell factor. A three-dimensional soil wedge model of soil failure was found to have moderate agreement with the total and horizontal forces and poor agreement with the vertical force. The model did not accurately reflect the effect of speed on the total, horizontal and vertical forces in these soils.

INTRODUCTION

The practice of subsoiling is usually carried out to improve the tilth and hydrologic characteristics of compacted soils. Subsoiling in pedogenetically compacted soils is a very high draft operation. The draft and efficiency of the operation can be affected by a number of operating characteristics such as soil type, soil moisture, soil strength, tool width and tool speed.

The relationship between tool speed and draft, for simple tools such as chisels and subsoilers, has been reported by a number of sources. Dransfield et al. (1964) reported observing no relationship between draft and speed in a loose sandy soil. The American Society of Agricultural Engineers (ASAE 1983) provides an equation for the draft of subsoilers in relation to depth, but speed is not included. A linear relationship between draft and speed has frequently been reported (Payne 1956; Rowe and Barnes 1961; Gill and Vanden Berg 1968; ASAE 1983; Bloome et al. 1983; Summers et al. 1986). A second-order polynomial equation has also been stated (Siemens et al. 1965; Luth and Wismer 1971; Pyl'nik 1978; Stafford 1979; Upadhyaya et al. 1984; McKyes 1985;). As well, the relationship has been reported as a decaying exponential equation for wet soils (Stafford 1979; McKyes 1985).

An increase in draft force with an increase in tool speed has been explained by a corresponding increase in the soil shear strength due to an increase in the shear rate (Rowe and Barnes 1961). However, it has been shown that the strength of frictional soils does not increase greatly with increasing shear rate (Stafford and Tanner 1983; McKyes 1985). This indicates that in cohesionless soils, the increase in draft associated with an increase in speed is attributable to an increase in the inertial forces required to move the soil blocks and, therefore, draft should increase with the square of the speed. In cohesive soils, soil strength increases logarithmically with increasing shear rate (Stafford and Tanner 1983) and, therefore, the draft force is related to tool speed by a decaying exponential function (Stafford 1979; McKyes 1985).

The relationship between draft and speed has also been found to depend on the mode of failure (Stafford 1984) which, in turn, is dependent on the soil strength, soil moisture and blade design (Stafford and Tanner 1976; Stafford 1981). The mode of failure can be brittle failure or flow failure (Stafford 1984) and these modes result in two distinct draft-speed relationships (Stafford 1979). In a uniform soil, with a flat blade, the mode of failure, and therefore the nature of the draft-speed relationship, is dependent on soil moisture (Stafford 1979). The draft-speed relationship under brittle failure is a second-order polynomial while that under flow failure is a decaying exponential (Stafford 1984). High tool speed can contribute to the inducement of flow failure (Stafford 1984). A change in the failure mechanism results in a discontinuity in the draft-speed relationship when the method of soil failure changes from brittle to flow failure at high speed (Stafford 1984). At speeds above 5 m/s, the draft force appears to be independent of speed (Stafford 1979). Stafford (1979) reported that the specific draft increased with increasing tool speed.

Draft forces on tillage tools have also been reported as being cyclical in nature (Upadhyaya et al. 1987) and speed has been shown to have an effect on these cyclical variations (Stafford 1981; Upadhyaya et al. 1987).

The relationship between tool speed and the area of soil disturbed by the blade has been reported as a linear function (Stafford 1979) but with only a 50% increase in area over a speed range of 0-5 m/s. Payne (1956) reported no effect of speed on the area of soil disturbed by the tool. Increased tool speed has been shown to increase the degree of soil break up within the disturbed area (Payne 1956; Pyl'nik 1978). It was also observed that speed had no effect on the movement of soil horizons within the area disturbed (Pyl'nik 1978).

The objective of this experiment was to determine, under field conditions in two compact soils, the effect of tool speed on the vertical, horizontal and total forces on a subsoiler tine; on the moment applied to the tine; on the soil areas heaved and disturbed; on the total soil area; on the specific resistance; and to compare the vertical, horizontal and total forces to values predicted by a three-dimensional model of soil wedge failure.

MATERIALS AND METHODS

The experiments were carried out in two soil types, selected for their widely different mechanical properties; however both are pedogenetically compacted soils. These soils can present problems for agriculture and subsoiling may provide some relief (Saini 1980). One soil was a Fundy clay loam, an Orthic Luvic Gleysol (Soil 1), which has an underlying clay subsoil starting at 40 cm deep. The other soil was a Research Station sandy loam, a Gleyed Dystric Brunisol (Soil 2), which maintains a relatively constant texture with depth, although the subsoil contains high levels of coarse fragments (Rees and Fahmy 1984).

The average physical properties of these soils are shown in Table I. Owen (1988) tested these two soils for several mechanical properties and the results are shown in Table II. The peak friction angle (ϕ_p) and the peak cohesion (C_p) represent the maximum strength of the soils at failure based on the Coulomb equation. Soil 2 was found to be incapable of developing a peak strength, typical of sandy soils. The ultimate friction angle (ϕ_u) and the ultimate cohesion (C_u) represent the maximum strength of the soil just after failure. δ represents the soil-to-metal friction angle and C_a is the adhesion. The gravimetric moisture content of Soil 1 was measured at the time of subsoiling and found to be 22.6 and 19.0% at depths of 100 and 400 mm, respectively, based on 21 samples. In Soil 2, the moisture content was 30.5 and 16.7% at depths of 100 and 400 mm, respectively, based on 12 samples.

To carry out the tillage operations, a vertical rigid tillage tool, with a width of 40 mm and a maximum depth of 1.10 m, was mounted on a trailed tool bar system as shown in Fig. 1. Depth was controlled by hydraulically moving the ground wheels with respect to the tool bar. The tine was mounted in the center of the rear tool bar and was operated at a nominal depth of 450 mm for all tests. A toe piece share, with a width of 75 mm and a rake angle of 20°, was installed on the tine as shown in Fig. 2. Wings, with a sweep angle of 40°, slope angle of 17° measured from the horizontal, and a rake angle of 16° measured from the axis of motion, were also installed. The wings were mounted just behind the share and gave an overall width of 260 mm, wing tip to wing tip.

An instrumentation system had been installed on the trailed tool bar system and was used to record several operating parameters of the tillage tool. The instrumentation system recorded the vertical force (V), horizontal force in the direction of travel (H), and the moment (M) in the plane of these forces as applied to the tine. These values were measured using an octagonal ring transducer rigidly mounted on the tool bar. Wheel speed was measured by a proximity switch and gear system mounted on an axle of the trailed tool bar system. Operating depth was determined by a linear displacement transducer which measured an angle between the tool bar and one of the axle supports used to adjust the depth. The data were recorded at 100 Hz for a fixed time period of 30 s under constant velocity. This resulted in 2999 readings per channel. Further details of this system can be found in Owen et al. (1987). The values used in the analysis were the averages of the 2999 readings for each treatment. The total force on the tine (P) was calculated from the vectorial sum of the vertical and horizontal forces.

Table I. Soil physical properties†

Soil	Horizon	Depth (mm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (t/m^3)
Soil 1	Ap	0–220	26.0	43.2	30.8	
	Aeg	220–300	34.3	46.4	19.3	1.67
	Bg	300–400	23.3	45.5	31.2	
	Btgl	400–770	6.2	36.3	57.5	1.59
	Btg2	770+	3.1	34.0	62.9	
Soil 2	Ap	0–210	40.5	48.3	11.2	1.28
	Bfjgj	210–360	53.3	40.8	5.9	
	2BCgj	360–510	56.3	37.0	6.7	1.87
	2Cgj	510–800	58.7	34.8	6.4	
	2C	800+	51.7	41.4	6.8	

†From Rees and Fahmy (1984).

Pits were dug perpendicular to the line of pull to a depth of 1.0 m by excavating with a backhoe working along the line of pull of the tractor. The soil face was then cut back a further 100 mm with a hand shovel.

Profiles of the soil heave and soil area disturbed were determined using a profile meter which enabled measurements every 10 mm horizontally, to 1 m on either side of the path of the tine, similar to that used by Owen (1988). The areas heaved (Ah) and disturbed (Ad) were determined by summation of the readings across the width. The width of disturbance (W) was taken as the width of the area disturbed at the soil surface, as indicated by the profile meter. The total area (At) is the sum of the disturbed and heaved areas. The swell factor (Sf) was determined from the ratio of the areas disturbed and heaved to the area disturbed minus one, all multiplied by 100 (McKyes 1985). The specific resistance (SR) was derived from the ratio of the horizontal force to the soil area disturbed.

The subsoiler was pulled with a 104-kW crawler tractor and was operated over the maximum speed range of the tractor, approximately 0–2 m/s. Twenty-six random speeds were used for the force measurements in each soil and the tests were performed randomly throughout each site. In 22 of the plots in each soil, soil disturbance data were collected.

Stepwise regression analysis was performed to determine the effect of speed and soil on the dependent variables $V, H, P, M, Ah, Ad, At, W, Sf$, and SR.

After preliminary observation of the data, it was decided to perform stepwise regression on a polynomial equation of the general form

$$Y = a_0 + a_1 \times \mathrm{SOIL} + a_2 \times \mathrm{SPD} + a_3 \times \mathrm{SOIL} \times \mathrm{SPD} + a_4 \times \mathrm{SPD}^2 + a_5 \times \mathrm{SOIL} \times \mathrm{SPD}^2 \qquad (1)$$

where:

Y = dependent variable;
$a_{0 \ldots 5}$ = regression coefficients;
SOIL = soil type; and
SPD = tool speed (m/s).

Table II. Soil mechanical properties†

Soil	MC (%)	ϕ_p^0	C_p (kPa)	ϕ_u^0	C_u (kPa)	δ^0	C_a (kPa)	LL (%)	PL (%)
Soil 1									
Topsoil	29	41.8	30.4	43.8	5.1	18.8	3.7	33.31	27.14
Subsoil	24	45.4	50.4	42.9	5.8	12.3	8.9	34.49	24.04
Soil 2									
Topsoil	31	–	–	42.3	5.9	20.1	4.1	32.37	N.P.‡
Subsoil	25	–	–	39.7	5.4	21.1	3.4	16.46	N.P.

†Mean of six measurements (Owen 1988).
‡Nonplastic.

Figure 1. Trailed tool bar subsoiler.

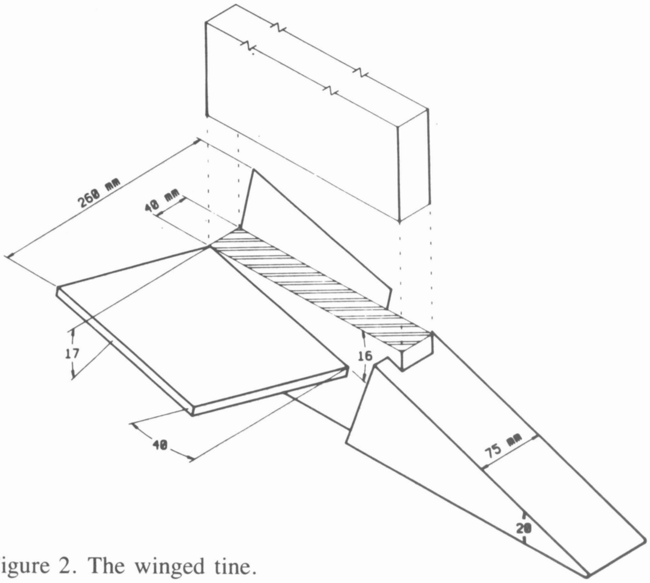

Figure 2. The winged tine.

This equation includes the main effects of soil, speed and speed squared and the interactions of soil × speed and soil × (speed squared). From this form of regression analysis, it could be determined if the response to speed was similar or different in trend in the two soils. A difference in the response to speed between the two soil types would be represented by significant coefficients for the interactive terms (a_3 and a_5 in Eq. 1). Soil was treated as a qualitative variable by assigning the orthogonal values of 1 and 0 to Soil 1 and Soil 2, respectively.

Ah, Ad, At, W and *Sf* were then subjected to an analysis of variance and Duncan's multiple range test to determine if soil alone had an effect on those parameters.

Equations were developed from a model to predict the effect of tool speed on the total, horizontal and vertical forces. The model is based on three dimensional soil wedges and is in the general form of the Reece earth moving equation. The model was developed by McKyes (1978) and an additional term was added (McKyes 1985) to accommodate the effects of tool speed as shown in Eq. 2.

$$P = (\rho g d^2 N\gamma + CdN_c + C_a dN_{ca} + qdN_q + \rho SPD^2 dN_a)W \quad (2)$$

where:

ρ = initial soil density (kg/m^3);
g = gravity (m/s^2);
d = operating depth (m);
C = soil cohesion (kPa);
C_a = soil adhesion (kPa);
q = surcharge pressure (kPa);
W = tool width (m);
N = dimensionless factors relating to ϕ, δ and the rake angle; and
SPD = tool speed, (m/s)

Using an iterative BASIC language computer program, Eq. 2 was solved for all terms except *SPD* to develop equations relating tool speed to the total force. The soil parameters were drawn from Table I and from the topsoil values in Table II. The tool width for Eq. 2 was taken as the effective width of the blade, 260 mm, and the rake angle was 16°.

McKyes (1985) also presented equations to resolve the total force into the horizontal and vertical components as per Eqs. 3 and 4.

$$H = P_{\sin} (\alpha + \delta) + C_a + C_a dW cot\ (\alpha) \quad (3)$$

$$V = P_{\cos} (\alpha + \delta) - C_a dW \quad (4)$$

where:

α = rake angle.

Equations 3 and 4 were then solved to develop equations relating tool speed to the horizontal and vertical forces. The predicted values for *P, H* and *V* were plotted with the regressed values for comparison.

RESULTS AND DISCUSSION

Regressed equations were accepted when all of the included coefficients were significant (0.05 level) and the results are shown in Table III. The results were such that all of the coefficients shown in Table III were highly significant (0.01).

Speed and soil significantly affected the dependent variables *V, H, P, M,* and *SR*. Speed had a linear effect on the vertical force, *V*, as indicated by the highly significant regression coefficient a_2 in Table III. Soil also had an effect on *V*, shown by the highly significant coefficient a_1. No interaction between speed and soil was present, indicating a similar form of response in both soils. The simple linear response of *V* to speed is shown in Fig. 3 for both soil types.

Speed squared and soil affected the horizontal force, *H*, as shown by the highly significant coefficients a_4 and a_1 in Table III. Again, no interactions between independent variables were present indicating a similar trend in both soil types even though the two soils have very different peak cohesions (Table II). These results are consistent with those of Stafford (1984) as the operation was performed above the critical depth (Owen 1988) and the mode of failure is brittle. The coefficient a_4 is small compared to a_0 and a_1 and therefore the effect of speed squared on *H*, in the speed range tested, is small. The effect of soil was to offset the equations in the two soils with Soil 1 having the higher H values and is shown in Fig. 4.

Table III. Significant regression coefficients for Eq. 1

Dependent variable	a_0	a_1	a_2	a_3	a_4	a_5	R^2
V	−0.34	1.12	0.88	-	-	-	0.45
H	17.37	3.22	-	-	0.87	-	0.59
P	17.39	3.25	-	-	0.89	-	0.60
M	24.66	3.64	-	-	1.00	-	0.49
SR	83.36	11.75	-	-	6.79	-	0.41

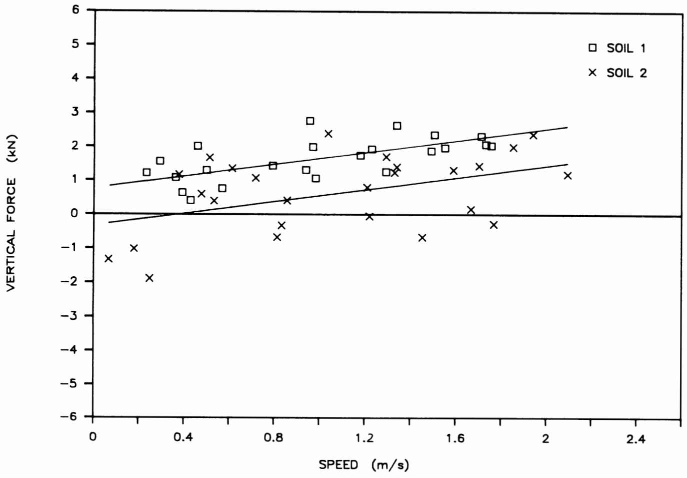

Figure 3. Effect of speed on the vertical force.

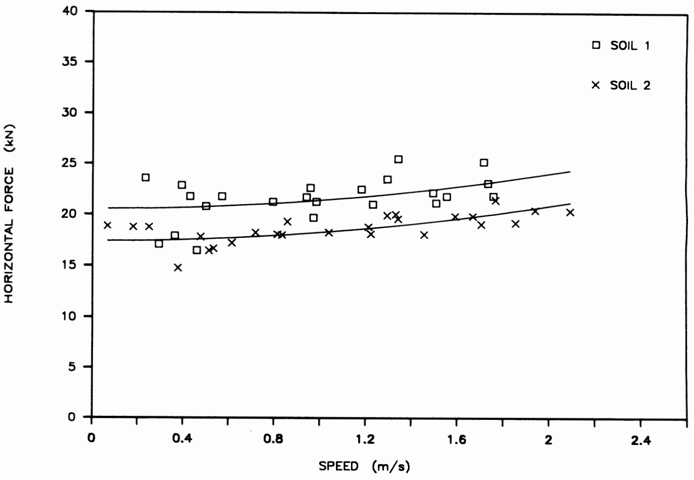

Figure 4. Effect of speed on the horizontal force.

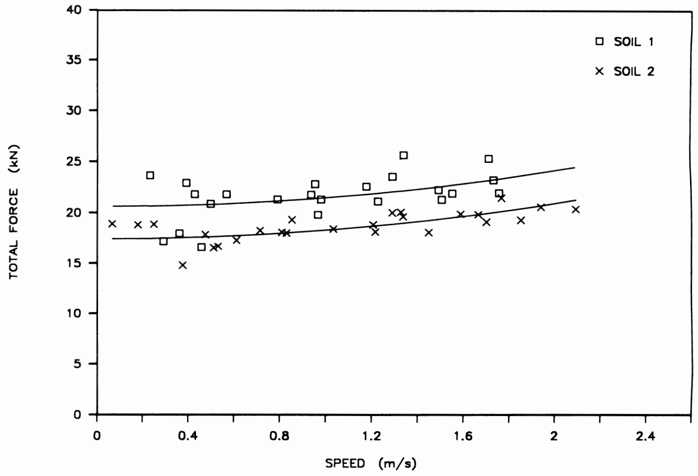

Figure 5. Effect of speed on the total force.

The response of the total force, *P*, to speed and soil is similar to that of H and is shown in Fig. 5. This is to be expected as *P* is the vectorial sum of *V* and *H* and *H* is much larger than *V* in magnitude (Figs. 3 and 4) and, therefore, is the predominant input. Similarly, the moment, *M*, is developed by the applications of *V* and *H* and because *H* is much larger than *V* and has a larger moment arm, *H* dominates *M*. Therefore, the response of *M* to speed is similar to that of *H* as shown in Fig. 6. The specific resistance is also highly dependent on the horizontal force and this is reflected in the regression equation (Table III) and Fig. 7.

Overall, soil consistently had a main effect on the forces, the moment and the specific resistance. This effect resulted in greater magnitudes of these dependent variables in the clay loam soil. The lack of interaction between soil and speed indicates that the response of the dependent parameters is the same in trend in both soils even though the soils have different mechanical properties.

The coefficient of determination (R^2), which ranged between 0.40 and 0.60 for all equations (Table III), is moderate and insufficient for modelling or prediction. However, these equations do reveal that speed and soil have highly significant effects on the dependent variables *V, H, P, M* and *SR*.

The effect of tool speed on these parameters, while highly significant, is quite small in relation to their magnitudes in the

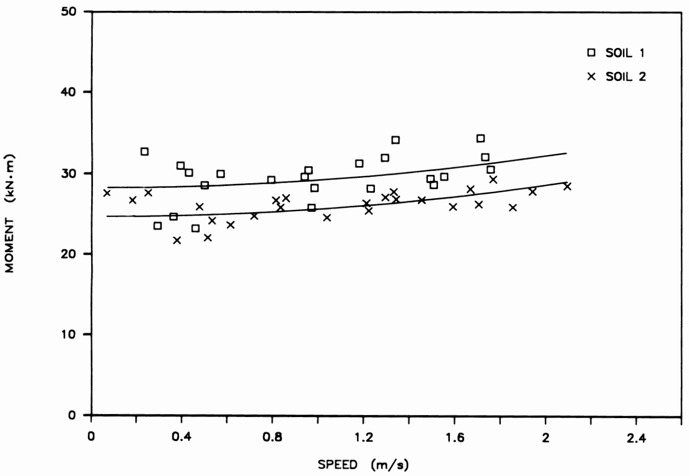

Figure 6. Effect of speed on the moment.

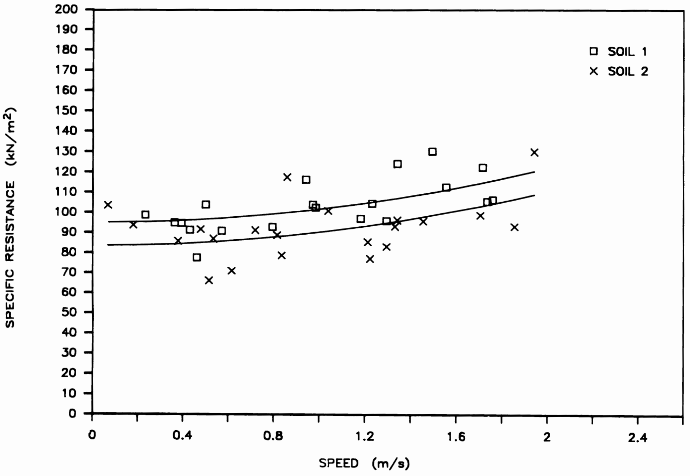

Figure 7. Effect of speed on the specific resistance.

speed range tested. Using Soil 1 and the regressed equation for the horizontal force, *H*, = 20.6 kN at a speed of 0.07 m/s and *H* = 22.3 kN at a speed of 2.00 m/s, a difference of only 8.5% over the entire speed range of the crawler tractor.

None of the independent variables tested had significant coefficients for the parameters of soil disturbance, *Ah, Ad, At, W* and *Sf*. This indicates that neither tool speed nor soil had a significant effect on these parameters under the conditions tested, possibly due to the wide variation in the readings. The measurement of *Ah, Ad, At, W* and *Sf* can be highly subjective depending on the soil conditions. The results of the Duncan's multiple range test indicate that soil type alone had no significant effect. The means of *Ah, Ad, At, W* and *Sf* and their standard deviations are shown in Table IV.

The regression curves and the predicted values of P are shown in Fig. 8. Equation 2 predicted higher values of *P* in the clay loam than in those in the sandy loam as was found by the regression analysis. However, the model overestimated *P* in the clay loam by approximately 32% and underestimated *P* in the sandy loam by approximately 37% as compared to the regression. The model underestimated the effect of tool speed on *P* when compared to the regression lines and resulted in a very nearly horizontal line (Fig. 8). The predicted values of *H*, from Eq. 3, were lower than the regression curves, by 16 and 53% in the clay and sandy loams, respectively, as shown in Fig. 9. The effect of tool speed on *H* as determined by the soil wedge model was very small. Agreement between Eq. 4 and the regression curves was very poor as the model overestimated the vertical force as shown in Fig. 10. In all three cases, the model appeared to give insufficient weight to the effect of tool speed when compared to the regression curves.

Table IV. Average parameters of soil disturbance

Parameter	Mean†	Standard deviation	Units
Ah	0.066	0.018	m^2
Ad	0.209	0.024	m^2
At	0.275	0.031	m^2
W	0.93	0.01	m
Sf	32.15	9.70	%

†Mean of 43 samples.

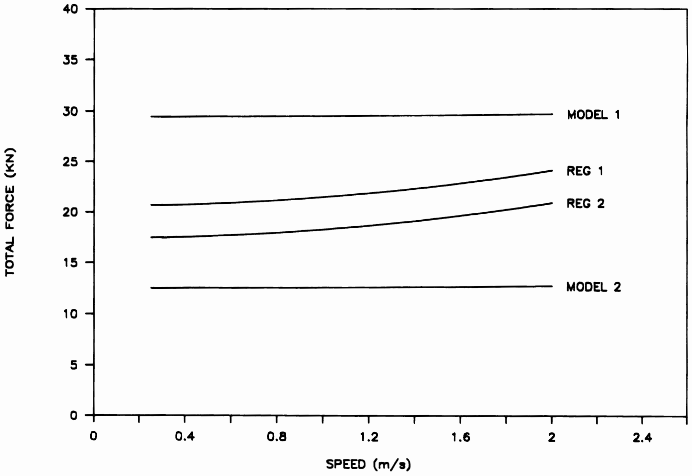

Figure 8. Soil wedge model prediction of P and regression lines. Model 1 = Model in soil 1. Model 2 = Model in soil 2. Reg 1 = Measurement regression line in soil 1. Reg 2 = Measurement regression line in soil 2.

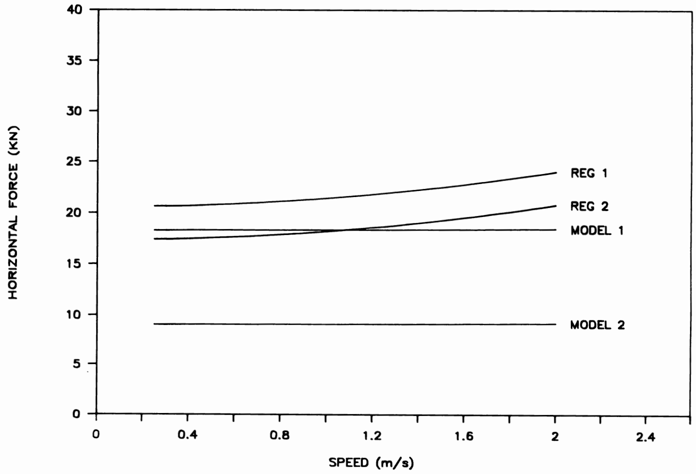

Figure 9. Soil wedge model prediction of H and regression lines. Model 1 = Model in soil 1. Model 2 = Model in soil 2. Reg 1 = Measurement regression line in soil 1. Reg 2 = Measurement regression line in soil 2.

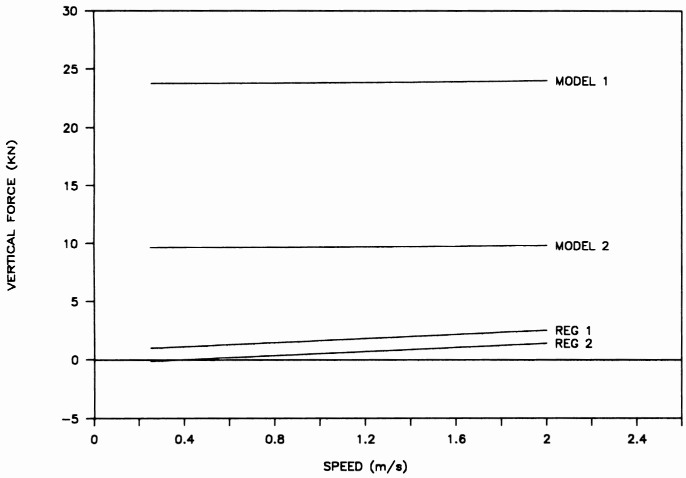

Figure 10. Soil wedge model prediction of V and regression lines. Model 1 = Model in soil 1. Model 2 = Model in soil 2. Reg 1 = Measurement regression line in soil 1. Reg 2 = Measurement regression line in soil 2.

CONCLUSIONS

In the soils tested, the magnitude of the vertical force on the tine increased significantly with an increase in the tool speed and the relationship was linear. The horizontal and total forces varied significantly with the square of tool speed. The moment on the tool and the specific resistance also varied with the square of the tool speed. The effect of tool speed on these parameters was small over the range tested.

Tool speed had no significant effect on the areas of disturbance, *Ah, Ad* and *At*. The width of disturbance and the swell factor were also unaffected by tool speed under the conditions examined. Soil type did not have a significant effect on *Ah, Ad, At, W* and *Sf* under the conditions examined.

The three-dimensional soil wedge model of soil failure had moderate agreement with the data for the total and horizontal forces and poor agreement with that for the vertical force. The model did not adequately reflect the effect of speed on *P, H* and *V* in these two pedogenetically compacted soils.

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