ESTIMATING TRACTOR DRAWBAR PULL FROM SOIL PROPERTIES

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INTRODUCTION

The ability to predict the performance of a tractor in the field has long been a goal of the agricultural engineer. Extension personnel, and some farmers, have been guided by taking some percentage of the drawbar pull reported by the Nebraska Tractor Tests. Friesen and Domier (2) more recently suggest the use of the coefficient of traction (static) as a guide. In general, farmers solve this problem on a trial and error basis. Only when a tractor of a different size is purchased is difficulty experienced and then questions of tire size, amount of ballast, allowable slippage, etc., are raised. Reece (8) has stated, "The principal problem is to determine the maximum thrust that the tractor can exert and the way in which it grows with slip". He has modified Coulomb's equation for shear stress as follows:

$$P = (aC + R \tan \phi)X \quad \ldots\ldots\ldots\ldots 1$$

where P = soil thrust (lbs.)
a = tire contact area (sq. in.)
C = cohesion (psi)
R = dynamic soil reaction, driving wheels (lbs.)
ϕ = internal angle of friction (degrees)
X = slip function.

The derivation of the slip function (X) cannot be noted here but it is essentially a function of the slippage and the length of the tire contact, L. In addition, Reece has determined values of the slip function at maximum drawbar horsepower as a function of L. This provides a logical basis for comparing tractive performance. Reece concludes that the theory is oversimplified but feels it is probably adequate for evaluating two wheel versus four wheel drive tractors. In view of this it is also probably adequate to evaluate different sizes of two wheel drive tractors and even different tire sizes and amounts of ballast. The latter are common queries of farmers because of the options provided by the tractor manufacturers.

Unfortunately equation 1 cannot be applied for local soils as the soil dynamic parameters C and ϕ are unknown. Rutledge and MacHardy (9) in their study on the influence of weather on field tractability circumvented this difficulty by using a linear relationship between the shear force and the plastic parameters of soil developed by Nichol's (6). For their purpose they chose the relationship for soils within the plastic range. Since tillage is not normally carried out in this range Nichol's relationship for soils below the plastic range, which is noted below, is appropriate.

$$\tau = \frac{0.06M}{Pl}(Pn + 20) + \sigma + 0.6 \quad \ldots\ldots\ldots\ldots 2$$

where τ = shear stress (psi)
σ = normal stress (psi)
M = moisture content (%)
Pl = lower plastic limit
Pn = plasticity number = .6 (% clay) − 12

The distinct advantage for either relationship is that the plastic parameters are known for most of the soils in Alberta. Equation 1 then becomes:

$$P = \left(R + .6a + \frac{.06aM}{Pl}(.6c + 8)\right)X \quad \ldots\ldots\ldots\ldots 3$$

where c is the clay content of the soil in percent. With the exception of R, values required are readily available and appear in Tables 1 and 4.

TABLE I. MECHANICAL ANALYSIS OF ALBERTA SOILS (Ap horizon)*

Soil Zone	Soil Series	Soil Class	Mechanical Analysis %S	%Si	%C	Plasticity Number** Pn	Liquid Limit*** P_u
Brown	Cavendish	SL	77	11	12	-	19
	Foremost	L	45	35	20	0	29
	Seven Persons	C	18	32	50	18.0	46
Dark Brown	Carmangay	LS	81	10	9	-	19
	Granum	L	42	37	21	0.6	26
	Coaldale	CL-C	28	30	42	13.2	43
Thin Black	Irma	LS-SL	77	12	11	-	23
	Elnora	L	37	38	25	3.0	39
	Three Hills	C	16	36	58	22.8	59
Black	Peace Hills	LS	82	10	8	-	20
	Angus Ridge	L	42	33	25	3.0	42
	Malmo	SIC	15	35	50	18.0	60
Grey Wooded	Culp	LS	80	8	12	-	14
	Breton	L	42	36	22	1.2	26
	Maywood	CL-SICL	30	42	28	4.8	36

* Based on data obtained from the Department of Soil Science, University of Alberta.
** Calculated by the formula Pn = 0.6C-12
*** Although values are given for liquid limit for the soil classes LS-SL, it should be noted that the liquid limit for cohesionless soils is meaningless (5).

TABLE II. ANALYSIS OF VARIANCE OF THE DIRECT SHEAR RESULTS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Replicates	2	0.22	0.11	0.06
Soils (S)	1	951.06	951.06	490.24*
Moisture (M)	2	255.12	127.56	65.75*
Pressure (P)	2	230.44	115.22	59.39*
S x M	2	219.26	109.63	56.51*
S x P	2	59.89	29.94	15.43*
M x P	4	32.12	8.03	4.14*
S x M x P	4	7.14	1.78	0.92
Error	34	65.83	1.94	
Total	53	1,821.08	1.94	

* Significant at .01 probability level (10)

The validity of using Nichol's equation for soil strength is questioned in the light of recent investigations. Additional variables have been found which effect the shear strength. Hanson, Johnson and Young (4), for example, found that soil densities and loading velocities are significant. Vomcil and Chancellor (11) concluded that soil strength may change with water content in a manner not adequately described by the Atterberg limits (plastic parameters). These and other findings raise serious questions with respect to the relationship suggested by Nichols. On the other hand because of their simplicity it would be highly desirable if these equations could be applied to the practical problems of traction and tillage. In view of this a study to determine the practical limits of applying equation 2 (and therefore equation 3) was initiated.

EXPERIMENTAL PROCEDURE

A completely randomized factorial design was used for the experiment. It was a 2 × 3 × 3 factorial with the following levels:

Soil, $S = 2$: $i = 1,2$.

Moisture, $M = 3$: $j = 1 \dots 3$.

Normal stress, $\sigma = 3$: $k = 1 \dots 3$.

Replicates, $R = 3$: $l = 1 \dots 3$.

The complete mathematical description for any observation is

$$X_{ijkl} = \mu + S_i + M_j + \sigma_k + (SM)_{ij} + (S\sigma)_{ik} + (\sigma)_{jk} + (SM\sigma)_{ijk} + e_{ijkl} \quad \dots\dots\dots\dots 4$$

Since a fixed effects model was used (i.e. S, M and σ were fixed) the error term, e_{ijkl}, was used for testing main effects and interactions. The results of the statistical analysis appear in Table 2.

Equipment

Soil strength parameters which estimate the shear strength of a soil may be obtained by using several different soil shear devices. These include the triaxial shear, shear box and annular shear ring devices. A major disadvantage of these methods is that the strength for a given soil condition is a function of the device used to obtain it (1).

To meet the objectives of this study, a method of determining shearing stress in the soil while varying the soil properties and normal loading was required. It was also desired to achieve normal stresses of the approximate magnitude found under the traction wheel of a rubber tired tractor (3). The direct shear apparatus was chosen because it met the above requirements and in addition provided direct, easily computed results with a minimum of sample preparation.

The type of shear apparatus used was "box shear" (as distinct from ring shear) which consists basically of a rectangular box the top half of which can slide over the bottom half. The inside dimensions of the shear box were 2.37 × 2.37 inches giving an initial shear area of 5.62 in^2. The normal load on the failure plane was applied through a load cap by means of a crossbar and loading yoke. The base and load cap both had projecting metal gratings imbedded in the interior surfaces to ensure a uniform distribution of stress along the failure surface. Movements of the shear box were measured by means of dial gauges and the horizontal (shearing) force was measured by means of a calibrated proving ring.

Soil

Three Hills Clay and Elnora Loam, both cohesive soils, were chosen on the basis of widely separated clay contents and ready availability. Both were from the Ap horizon and had been ground to a maximum particle diameter of 2 mm. Particle size analyses for these and other soils in Alberta may be found in Table 1.

Preparation of the samples for the shear tests involved dividing each of the soil types into smaller lots and moisturizing them to the desired levels. The three soil moisture contents were approximately 20, 25 and 30 percent. These levels were selected to cover a range between the 1/3 atmosphere and 15 atmosphere percentages for both soil types. Samples of air-dry soil were placed in a container and sufficient water was added to achieve the desired moisture levels. Each moisturized sample was then mixed for 5 minutes before being transferred to a sealed plastic bag. The sealed samples were left for 7 days to allow the moisture to reach equilibrium within each sample.

Procedure

Soil samples were placed in the shear box removing the larger voids in the process. All samples were allowed to consolidate for 5 minutes while subject to the normal stress in order to achieve a uniform level of density. In all cases the rate of deformation had become extremely slow by the end of the 5-minute interval.

Each sample was sheared at a velocity of approximately 1.5 inch per minute and total shearing force was read from the calibrated proving ring dial. Shearing force was recorded at 1/25 inch increments of deformation until failure was reached. The strain rate of 1/5 inch per minute was chosen for this experiment because it was the fastest rate at which reliable readings could be taken from the shear apparatus.

The soil was then removed from the test apparatus and part of it used for moisture content determination. The results are given in Table 3 and are plotted on a graph of maximum

TABLE III. COMPARISON OF EXPERIMENTAL SHEAR STRENGTHS WITH CALCULATED VALUES

Soil Type	Moisture Content(%)	Normal Stress σ(psi)	Maximum Shear Strength Replicates τ(psi) 1	2	3	Maximum Shear Strength* (calculated) τ(psi)
Three Hills Clay	20.8	10.41	13.21	11.61	12.67	12.48
		14.83	15.71	16.43	17.14	16.90
		19.24	23.03	21.24	21.78	21.31
	26.4	10.41	12.14	13.03	14.46	12.88
		14.83	15.89	16.43	16.07	17.30
		19.24	20.71	19.64	18.92	21.70
	31.1	10.41	13.39	13.92	13.39	13.21
		14.83	17.32	15.89	16.07	17.63
		19.24	18.75	18.92	21.43	22.04
Elnora Loam	18.6	10.41	10.00	10.36	11.78	11.45
		14.83	13.93	13.04	13.21	16.14
		19.24	16.78	14.82	16.24	20.55
	23.2	10.41	6.43	6.78	6.25	11.90
		14.83	8.04	16.07**	7.32	16.32
		19.24	8.39	8.04	8.21	20.73
	28.7	10.41	3.21	2.32	2.50	12.12
		14.83	2.80	3.04	3.21	16.54
		19.24	3.32	3.39	4.11	20.95

* calculated from equation 2.

** rejected as in error.

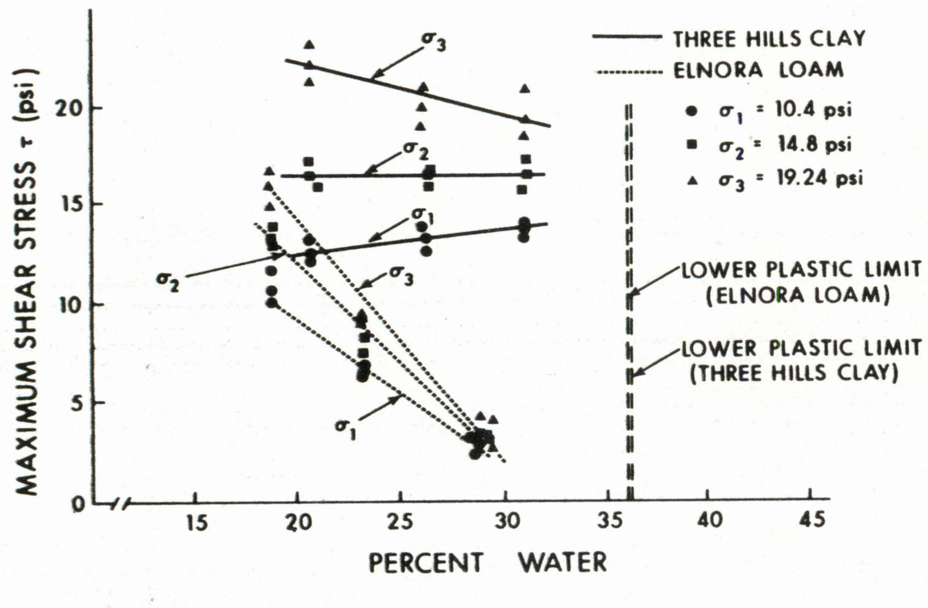

Figure 1. Maximum shear strengths of Three Hills clay and Elnora loam at different moisture contents and normal stresses.

shear stress versus soil moisture (Fig. 1). The maximum shear stresses as calculated from equation 2 appear in Table 3.

Mohr strength Envelopes (5) were plotted using the experimental data for each soil-moisture combination. Values of C and ϕ were obtained from these curves and are shown in Table 5.

RESULTS AND DISCUSSION

The analysis of variance (Table 2) indicates that not only the main effects but all the first order interactions were significant. The significance of the main effects indicated that the variations in shear strength between soil types, among the three moisture levels and among the three normal pressures were statistically significant. The first order interactions, soil × moisture, soil × pressure and moisture × pressure were also statistically significant. The latter indicates a differential response of the maximum shear stress depending on the interactions of the factors shown.

It can be seen (Table 3), (Fig. 1) that shear strength was considerably different for the two soils at approximately the same moisture content. The shear values incrèased directly with normal stress as expected. Increasing the moisture content at a given normal stress had much less effect on the shear strength of Three Hills Clay than on the Elnora Loam (Fig. 1). The relation of moisture content to maximum shear strength shown in this figure does not agree with the results obtained by Nichols. Nichols determined shear values from the Atterberg plasticity constants in such a way that the maximum shear values for the soil at any normal stress always occurred at the lower plastic limit. Instead they appear to correspond more closely with those obtained by Vomocil and Chancellor who concluded that the Atterberg limits do not adequately describe the role of water in its effects on soil strength.

It can be seen (Table 3) that experimental and calculated values were in fairly good agreement (at least for practical purposes) for the Three Hills Clay which had a plasticity number, Pn, of 22.8. Some of the calculated shear strengths were slightly higher than experimental values, particularly at higher normal stresses.

In the case of Elnora Loam, which had a plasticity number of 3.0, the calculated values for shear were considerably higher than the experimental values, especially at the higher moisture contents. Only at the lowest moisture contents and the lowest normal stress was there reasonable agreement. This might indicate (although statistical evidence is lacking) that the prediction equation would provide reasonably accurate strength values for Elnora Loam at moisture contents below 20%.

In view of the results obtained it appears that the soils (Table 1) can be divided into three arbitrary classes with respect to the applicability of equations 2 and 3.

1. Cohesionless soils ($Pn \approx 0$) – equation cannot be used.
2. Soils with an intermediate plastic range ($10 > Pn > 3$) – equation can be used for moisture contents up to approximately 20%.
3. Highly plastic soils ($PN > 10$) – equation can be used for any moisture content up to the lower plastic limit.

It should be noted, however, that this proposed grouping is based on plasticity number only, while equation 2 includes both plasticity number and lower plastic limit. Therefore, the reliability of such a grouping may be questionable. The soil types (Table 1) were arranged according to this classification (Table 4).

Table 5 indicates that the angle of internal friction, ϕ, decreases with increasing moisture content for both soil types. The cohesion intercept, however, varies directly with moisture content for the Three Hills Clay and inversely with moisture content for Elnora Loam. In the case of Three Hills Clay, the behavior of ϕ would indicate that at the lowest moisture content, the soil was behaving much like a dry granular material with practically all of the resistance to shear resulting from internal friction. At higher moisture contents, the soil exhibited greater plasticity with a resulting increase in the contribution of cohesion to shear strength. The Elnora Loam, on the other hand, has a much lower clay content and a lower liquid limit. Therefore, increases in moisture content within the moisture range studied resulted in reduced cohesion due to the relatively thicker adsorbed layers of water.

TABLE IV. PROPOSED GROUPING OF ALBERTA SOILS

Group*	Soil Series	Soil Class	Lower Plastic Limit Pl	Plasticity Number
I	Cavendish	SL	-	-
	Foremost	L	-	-
	Carmangay	LS	-	-
	Irma	LS-SL	-	-
	Peace Hills	LS	-	-
	Culp	LS	-	-
	Granum	L	-	0.6
	Breton	L	-	1.2
II	Elnora	L	36	3.0
	Angus Ridge	L	39	3.0
	Maywood	CL-SiCL	31	4.8
III	Coaldale	CL-C	30	13.2
	Seven Persons	C	28	18.0
	Malmo	SIC	42	18.0
	Three Hills	C	36	22.8

* Group I: equation 2 not applicable.
Group II: equation 2 applicable up to approximately 20% mc.
Group III: equation 2 applicable up to lower plastic limit.

TABLE V. EXPERIMENTAL VALUES OF C AND ϕ

Soil	Moisture Content (%)	C(psi)	ϕ(degrees)
Three Hills Clay	20.8	1.2	46
	26.4	5.6	36
	31.1	6.1	34
Elnora Loam	18.6	4.9	29
	23.2	4.1	12.5
	28.7	1.1	7

Payne and Fountain (7) report the typical values of C and ϕ to be 1.5 psi and 34½° for 50 widely differing soils. On this basis the cohesion and therefore the soil strength for the two soils tested appears large. This would also appear to be suggested by the work of Friesen and Domier (2). For a specific tire, soil and soil moisture, equation 3 can be reduced and solved for the slip function where:

$$X = P/R + \text{constant} \quad \ldots\ldots\ldots\ldots\ldots 5$$

This equation is now similar to that for determining the coefficient of traction C_t. To be the same, the rolling resistance would have to be subtracted from the soil thrust P, the weight transfer from R, and the constant equal to zero. The slip function for an 18.4 × 34 tire at 16% slip is approximately .72 whereas Friesen and Domier (2) report the maximum C_t to be .55.

The discrepancy appears to be due to the value of the soil strength as determined by the direct shear apparatus or predicted by equation 2. This may be partly explained by the fact that both the Atterberg limits and the experimental shear values were obtained from re-moulded soil samples while traction in the field depends on in place shear values. Consequently, soil may fail in a different manner under a traction tire than in the direct shear apparatus used. In view of the above, equation 3 should be limited for the present to comparisons of tractor sizes, tires and ballast and with certain soils and moisture contents.

CONCLUSIONS

Difficulties in predicting tractor performance in the field still remain. The results of this study show that Nichols' relationship for determining

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torily. Air temperatures of 50°F and 80 percent relative humidity have been held for 3 days with ± 0.5°F dry bulb and ± 1°F wet bulb variation. Temperatures of 100°F and relative humidities from 35 to 90 percent with ± 1°F dry bulb and ± 1.5°F wet bulb variation during a 3 day test have been obtained. Tests with birds in the chamber and at intermediate temperature and humidity values have been maintained for up to 6 weeks of continuous operation within the variation mentioned previously.

Surface temperature variations on the thermal radiation plates of ± 2.5°F were encountered. This was found to be the result of non uniform air velocities from the air inlets. Redesigning the air inlets for a more streamlined flow will alleviate this problem.

The water spray in addition to maintaining pre-selected humidities also removes fine dust, ammonia and excess carbon dioxide.

Temperatures of water entering and leaving heating and chilling coils, spray water, air entering and leaving the chamber, air leaving the fan and spray water zone were monitored by iron-constantan thermocouples connected to a 24 point potentiometric recorder.

A computer programme was developed to monitor the operation of the equipment. Water volume recorders for the heat exchange coils are required before the computer programme will be able to provide its full potential.

CONCLUSIONS

Equipment was developed to control the environment of a 16 square foot chamber for poultry by providing accurate control of thermal radiation, air temperature, wet bulb temperature, air velocity and light intensity. When all monitoring equipment for input and output factors is added, a complete energy balance can be determined. With accurate environment control, genotype by environment interactions can be evaluated.

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soil strength is not in complete agreement with results obtained from direct shear tests on two Alberta soils. Predicted tractor drawbar performance based on soil strength as determined by equation 2 or by the direct shear apparatus may not correspond to values obtained in actual field tests. However, comparisons of tractor sizes, tire sizes and ballast may be made provided the limitations of laboratory or calculated shear values are taken into consideration.

Better relationships of in situ soil strength to soil parameters are required to adequately describe tractor field performance.

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