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THE UNIVERSAL EARTHMOVING EQUATION APPLIED TO CHISEL PLOUGH WINGS

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Summary—This paper compares the results of tests which examined the effect of chisel plough wing geometry on tillage forces with those predicted by the Universal Earthmoving Equation as presented in E. McKyes' book *Soil Cutting and Tillage*, published by Elsevier (1985). The tests were conducted in the SAIT Tillage Test Track (an outside continuous soil bin which contains a sandy loam soil) and in two field soils, one a sandy loam and the other a red brown earth. The tests were conducted using a range of speeds from 5 to 15 km/h and at depths of 50 and 70 mm. The tests compared the effects of varying share wing width and rake angle. The comparison of the measured and predicted draft and vertical force responses showed a good correlation between the Universal Earthmoving Equation predictions and the measured width responses, but it did not always predict the correct rake angle responses.

INTRODUCTION

WITH INCREASING fuel costs and decreasing returns, farmers and tillage machinery manufacturers are looking for ways to reduce costs. One such way is through using more efficient ground engaging tools (especially for the current higher speed tillage) but these are yet to be designed and proven.

With experimentation being a slow and costly process, the ideal way to improve the design of plough shares would be to use a theory to predict tillage forces for varying share geometries. One such theory available to plough share designers and manufacturers is the Universal Earthmoving Equation which is presented in a usable form in the book *Soil Cutting and Tillage* by E. McKyes [1].

The aim of this paper was to compare the results of tests which examined the effect of chisel plough wing geometry on tillage forces with those predicted by the Universal Earthmoving Equation for various soil types in Australia.

THE UNIVERSAL EARTHMOVING EQUATION

One approach to modelling the tillage process is to consider the soil failure created by a tillage tool as a classical soil mechanics problem and apply the soil mechanics theories which were developed for failure predictions of footings and retaining walls.

Previous studies [2, 3] showed that by using these retaining wall and footing theories, prediction of soil failure for narrow tines and wide flat plates respectively can be achieved. Unfortunately, due to their complexity these models cannot easily be used.

To make these theories more readily usable, some simplifying assumptions about soil failure were made and the Fundamental Equation of Earthmoving Mechanics was

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proposed for all earthmoving processes [4]. The Fundamental Equation which Ref. [1] calls the Universal Earthmoving Equation (and as such will from here on be referred to as that) was based upon the soil weight, cohesion, adhesion and surcharge effects being algebraically additive.

To make the Universal Earthmoving Equation readily usable a book of solutions to earthmoving problems has been published [1]. In this book the Universal Earthmoving Equation was presented as follows.

Force, $P = (\gamma g d^2 N_\gamma + C d N_c + q d N_q + C_a d N_{ca}) w$

Draft Force, $H = P \sin(\alpha + \delta) + C_a d w \cot \alpha$

Vertical down force, $V = P \cos(\alpha + \delta) - C_a d w$

where γ = Soil density (kg/m^3);
g = Acceleration due to gravity (9.8 m/s^2);
d = Tillage depth (m);
C = Soil cohesive strength (Pa);
q = Surcharge pressure (Pa)—zero for this work;
C_a = Soil adhesive strength (Pa);
w = Tool width (m);
α = Rake angle (degrees);
δ = Soil to metal friction angle (degrees); assumed to be 2/3 soil friction angle (ϕ);
N_γ = Soil density factor;
N_c = Soil cohesive strength factor;
N_q = Surcharge factor;
N_{ca} = Soil adhesion factor.

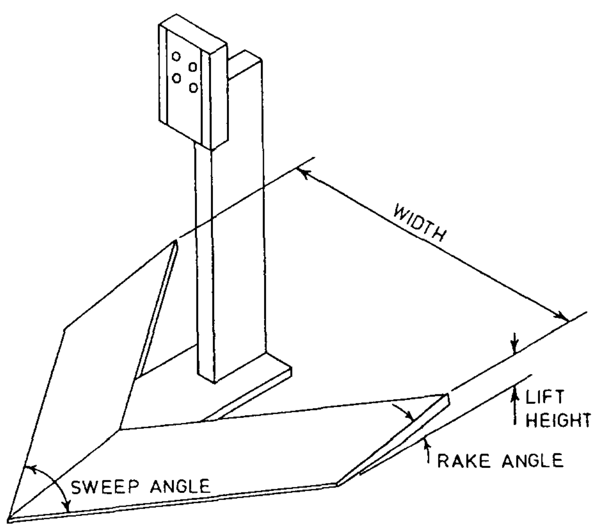

FIG. 1. Definition of share wing geometry.

THE EXPERIMENTAL SHARES

The experimental shares were based on the geometry of chisel plough shares currently used in Australia. It was observed that the chisel plough share could be simplified to consist of two inclined flat plates mounted on a vertical shank. To describe fully these flat plate wings, four geometric variables as shown in Fig. 1 were defined as follows.

Width: the width of the share wings, measured perpendicular to the direction of travel;

Lift Height: the vertical height of the share wing;

Rake Angle: the angle the share wing lifts the soil, measured in the direction of travel;

Sweep Angle: the angle enclosed by the two cutting edges of the share wings.

For the experiment, which was based on previous work [5], each geometric variable was varied individually about the current geometric shape. The nominal share geometries reported on here are shown in Table 1. The experimental shares all had a 3 mm high cutting edge, a 5° underside clearance and a 25 × 75 mm section shank whose leading edge of 25 mm width was set 295 mm behind the leading point.

TABLE 1. NOMINAL SHARE GEOMETRIES

	Width (mm)	Lift height (mm)	Rake angle (degrees)	Sweep angle (degrees)
Varying Width	200	32	10	70
	300	32	10	70
	400	32	10	70
	500	32	10	70
	600	32	10	70
Varying Rake Angle	400	32	6	70
	400	32	7.5	70
	400	32	10	70
	400	32	15	70
	400	32	25	70
	400	32	45	70

THE SAIT TILLAGE TEST TRACK

The SAIT Tillage Test Track [6] is a unique outside continuous soil bin with two straights of 50 m length which are joined by two curves of 50 m diameter. The test soil is 2.5 m wide and 0.3 m deep. An 80 kW tractor towing two trolleys, each capable of tillage testing and soil reconditioning, travels around the track at speeds up to 15 km/h.

For the experiment the Tillage Test Track was set up with the front trolley reconditioning the total width of soil by ploughing, grading out undulations and rolling. The rear trolley was used to measure the tillage tool's draft and vertical forces along with the speed and depth of tillage. The forces were measured using an extended octagonal ring transducer [7].

FIELD TESTING

The field testing was conducted at two sites near the towns of Avon and Hoyleton in South Australia's mid-North which is a mixed cereal and sheep farming region. In this area planting of crops occurs in the autumn after opening winter rains. In 1988 the opening rain occured in May after which the tests were conducted with seeding being carried out the following week.

The site at Avon on the Adelaide Plains had a sandy loam soil which was similar to that in the Tillage Test Track and was covered with the previous year's wheat stubble. The other site was at Hoyleton on the foothills of the Mount Lofty Ranges and had a hard setting red brown earth with very little wheat stubble left from the previous year's crop.

The field testing was conducted using the SAIT Single Tine Dynamometer [8] which is a purpose built four-wheeled trailer. Within the trailer a two-force measuring frame [8] was mounted to measure independently the draft and vertical forces on a tillage tool.

FORCE MEASUREMENT

For the tests, the signals from the force transducers were amplified using a fully active strain bridge and amplifier. The signals were digitised using a voltage to frequency converter and the pulses counted over a set period of time to give the average force.

The transducers were calibrated at the start and end of testing with no significant change in calibration noted.

SOIL PROPERTIES

During testing at the three sites, soil moisture content and bulk density were measured and samples of soil were taken for identification and testing. The soil classifications and soil properties obtained using a direct shear test are shown in Table 2. The direct shear tests were conducted according to the Australian Standard AS1289.E1.1–1977 using samples of soil made to the measured moisture contents and densities.

TEST PROCEDURE

The tests were conducted using a randomised split block design with three replications. At each of the sites the experiment was split into the geometric variations. Within each geometric variation the shares were tested at three speeds and one depth in a completely randomised order.

For the Tillage Test Track tests, speeds of 5, 10 and 12.5 km/h and a depth of 70 mm were used with the forces being averaged over a 40 m length of the 50 m straights. For

TABLE 2. SOIL PROPERTIES FOR THE THREE TEST SITES

Site	Moisture content (%)	Bulk density (kg/m^3)	Cohesive strength (kPa)	Friction angle (degrees)
Tillage test track (Sandy loam)	8	1900	6	45
Avon (Sandy loam)	5	1400	4	30
Hoyleton (Red brown earth)	26	1400	13	25

the field tests speeds of 5, 10 and 15 km/h and a depth of 50 mm were used with the forces being averaged over 50 m travel of a 70 m run.

Comparison of responses for the SAIT tillage test track

Comparisons of the measured draft and vertical force responses for varying width and rake angle at a range of speeds with those predicted using the Universal Earthmoving Equation for the SAIT Tillage Test Track are shown in Figs 2 and 3 respectively.

Tests using a modified direct shear apparatus to measure the soil/steel friction and adhesion showed the adhesion to be zero for the SAIT Tillage Test Track soil. The angle of soil/steel friction was measured to be 34° which is close to 30° (2/3 of the soil friction angle as assumed in [1]). Hence the SAIT Tillage Test Track predictions were calculated using zero soil adhesive strength.

The comparisons of width responses (Fig. 2) showed the Universal Earthmoving Equation to predict the draft force reasonably well, taking into account that the Universal

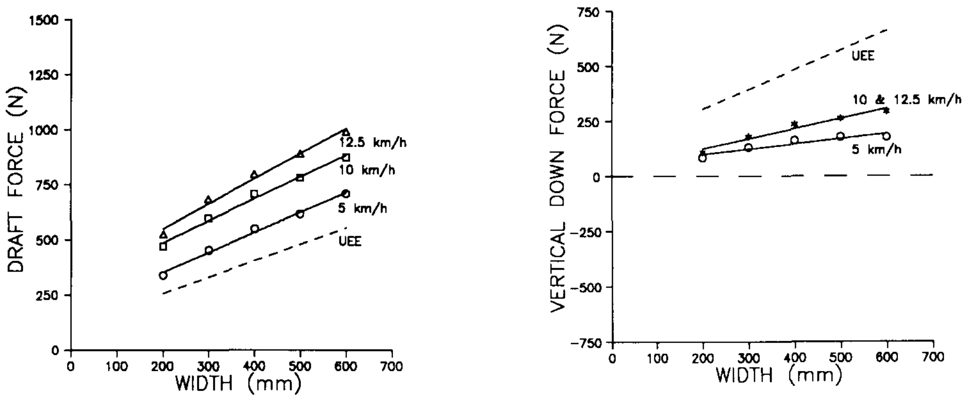

FIG. 2. Comparison of Universal Earthmoving Equation (UEE) predictions with measured width effects for the SAIT tillage test track tests (tool—70 mm depth, 32 mm lift height, 10° rake angle and 70° sweep angle).

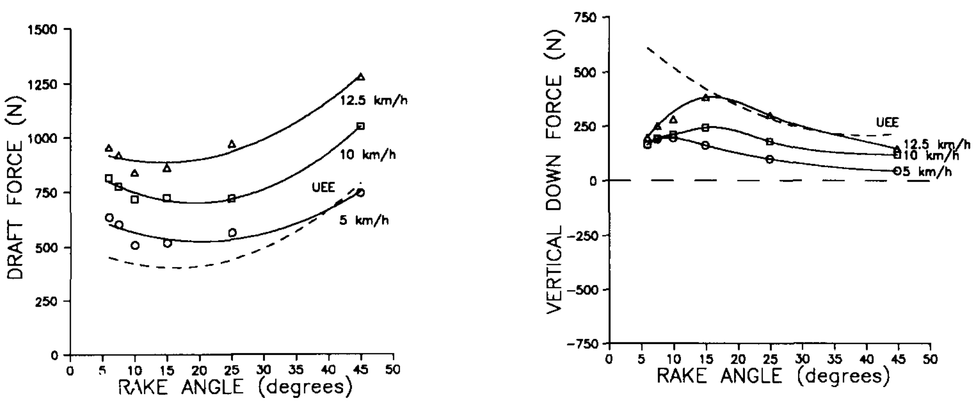

FIG. 3. Comparison of Universal Earthmoving Equation (UEE) predictions with measured rake angle effects for the SAIT tillage test track tests (tool—70 mm depth, 400 mm width, 32 mm lift height and 70° sweep angle).

Earthmoving Equation predicts for zero speed. However, it over-predicted the vertical down force.

As shown in Fig. 3 the Universal Earthmoving Equation predicted an optimum rake angle for minimum draft force in the range of 10 to 25° as observed for the varying rake angle tests in the SAIT Tillage Test Track. However, the Universal Earthmoving Equation did not predict the same vertical force response as was measured. The measured results showed there to be an optimum rake angle (in the range of 10 to 25°) for maximum vertical down force, while the Universal Earthmoving Equation predicted increased vertical down force with decreasing rake angle.

Comparison of responses for the tests at Avon

A comparison of the measured draft and vertical force responses for varying width and rake angle (at a range of speeds) with those predicted using the Universal Earthmoving Equation for the tests at Avon, are shown in Figs 4 and 5, respectively.

As the values for soil adhesive strength (C_a) were not measured but adhesion of soil

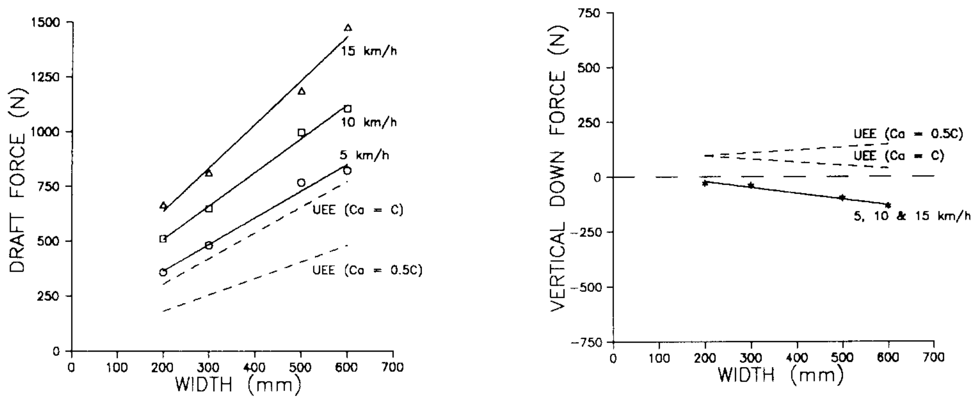

FIG. 4. Comparison of Universal Earthmoving Equation (UEE) predictions with measured width effects for the tests at Avon (tool—50 mm depth, 32 mm lift height, 10° rake angle and 70° sweep angle).

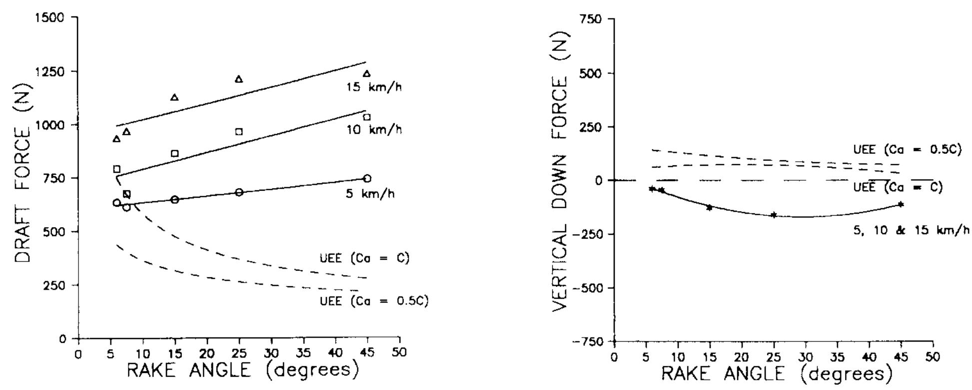

FIG. 5. Comparison of Universal Earthmoving Equation (UEE) predictions with measured rake angle effects for the tests at Avon (tool—50 mm depth, 400 mm width, 32 mm lift height and 70° sweep angle).

to the wings was observed, the Universal Earthmoving Equation predictions were made at two levels of C_a. These were, the adhesive strength equals the cohesive strength and the adhesive strength equals half of the cohesive strength.

Figure 4 of draft and vertical responses for varying width shows a correlation between the measured and predicted responses but the Universal Earthmoving Equation over predicted the vertical down force.

Figure 5 of draft and vertical force responses for varying rake angle shows the measured draft force increasing with rake angle while the Universal Earthmoving Equation predicted increasing rake angle to decrease the draft force. For the vertical force responses, the Universal Earthmoving Equation again over-predicted the vertical down force.

Comparison of responses for the tests at Hoyleton

Comparisons of the measured draft and vertical force responses with those predicted by the Universal Earthmoving Equation for varying width and rake angle, for the tests conducted at Hoyleton, are shown in Figs 6 and 7, respectively.

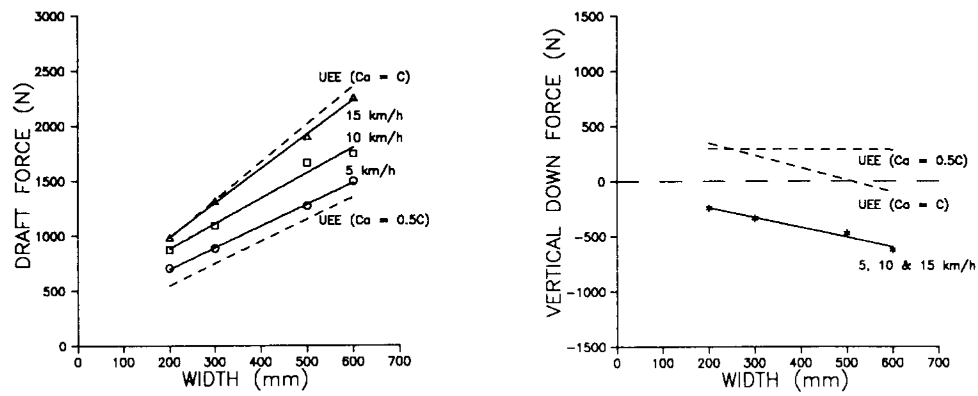

FIG. 6. Comparison of Universal Earthmoving Equation (UEE) predictions with measured width effects for the tests at Hoyleton (tool—50 mm depth, 32 mm lift height, 10° rake angle and 70° sweep angle).

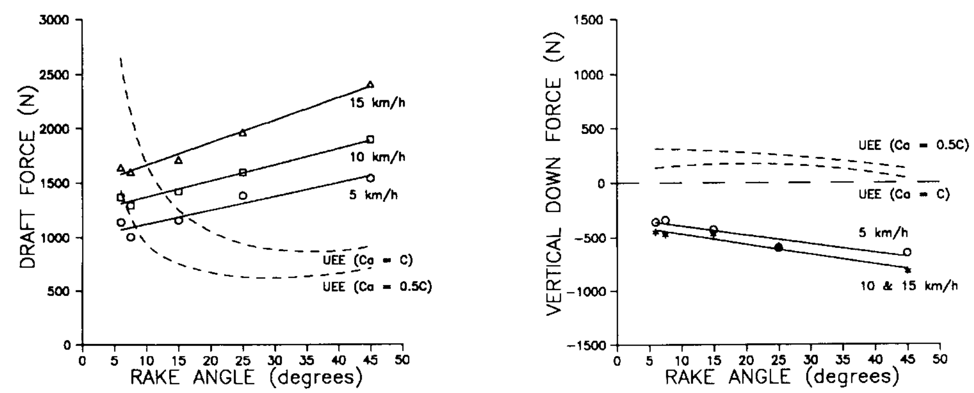

FIG. 7. Comparison of Universal Earthmoving Equation (UEE) predictions with measured rake angle effects for the tests at Hoyleton (tool—50 mm depth, 400 mm width, 32 mm lift height and 70° sweep angle).

Similar to the Avon results, the Hoyleton Universal Earthmoving Equation predictions were calculated at two levels of soil adhesive strength. As shown in Figs 6 and 7 the level of $C_a = 0.5C$ gave the better prediction.

For the rake angle effects, the Universal Earthmoving Equation did not predict the same draft force response as was measured for varying rake angle. It showed the least draft force at the higher rake angles while the measured results showed least draft force for the lower rake angles. For the vertical force it predicted a similar type of response but again it was over-predicted in a downwards direction.

OTHER FACTORS THAT AFFECT TILLAGE FORCES

In addition to speed (as shown in Figs 2–7), the other geometry factors of lift height and sweep angle have also been observed to have effects on the draft and vertical forces [9]. Of these factors the sweep angle had the greatest effect (through altering the soil failure, length of the cutting edge and soil flow over the wing at higher speeds) and its inclusion on the experimental shares (which had a 70° sweep angle whereas the Universal Earthmoving Equation assumes 180°) may be one reason why there were differences between the measured and predicted values. It is interesting to note that for the tests at Hoyleton (which had the worst correlation between measured and predicted rake angle responses) the sweep angle had its greatest effect. At Hoyleton increasing the sweep angle reduced the draft force and increased the vertical down force as shown in Ref. [9].

Further work is continuing by the authors to study the effect of cutting edge geometry on tillage forces. These tests are showing that the inclusion of the 3 mm high vertical cutting edge on the experimental shares would increase the draft force and reduce the vertical down force which would act to bring closer together the Universal Earthmoving Equation predictions and the measured values.

CONCLUSIONS

The comparison of measured width effects on draft and vertical forces of shallow working chisel plough wings with those predicted by the Universal Earthmoving Equation showed a good correlation for the three soils evaluated.

For varying rake angle, the controlled SAIT Tillage Test Track tests had a good correlation between the measured and predicted draft force results with both showing a minimum in draft force for rake angles in the range of 10 to 25°. However, the correlation did not continue for the vertical force results in the SAIT Tillage Test Track or for the draft and vertical force results at the field sites at Avon and Hoyleton.

In all cases the vertical force was over predicted in a downwards direction.

Hence, the Universal Earthmoving Equation in the form presented in the book *Soil Cutting and Tillage* [1] can give some useful indications as to the magnitudes of the tillage forces. However, its usefulness for the optimisation of designs for chisel plough wings for Australian conditions appears to be limited.

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