

# AN ANALYSIS OF FORCES ON CULTIVATOR SWEEPS AND SPIKES

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This paper describes the results of extensive field measurements of the lateral, vertical and draft forces that are caused by cultivation. Two types of cultivator tools were evaluated; sweeps both in a leading and overlapped trailing position, and a spike. It is shown that draft forces increased with depth of tillage as did the vertical force, but the latter to a lesser degree. Where a trailing sweep was overlapped by a leading sweep the lateral force on the trailing sweep measured as much as 20% of the draft force. There was little correlation of forces with speed in the range of 6-12 km/h tested. All tests were conducted in dry hard-packed soils classified as clay-loam.

## INTRODUCTION

When cultivator sweeps or shovel tools are used for deep soil penetration in place of standard moldboard plows, the loads imposed on the cultivator components can be large and, in some cases, may be more than the manufacturer anticipated in the original design. This has resulted in the need for a better understanding of what forces exist under such severe operating conditions so that, if necessary, appropriate changes in design can be made. This paper describes the results of a series of field tests in Alberta over five different and widely separated localities in which the forces were measured on cultivator sweeps, in both a leading and trailing overlapped condition, and on spikes.

Numerous investigations into the interaction of simple cultivation implements and soil have been carried out and various two- and three-dimensional mathematical models have been proposed. Much of this data has been obtained in the laboratory under closely controlled conditions and while it has assisted in a better understanding of the mechanisms of cultivation there has been less application to actual cultivator operations including the interaction between pairs of sweeps acting in tandem. With the increased use of the cultivator for primary and secondary tillage, it is suggested that more data be available to enable designers to understand better the actual loading conditions under which these implements are to function.

Clyde (1936) reported that field testing of cultivators consisted of measuring vertical and longitudinal forces. Shovel tools, 51 mm in width, were tested at depths less than 127 mm with presumably no wing overlap and at the same speed. Draft loads from 93 to 512 N were measured with the vertical about 19% of the draft load. Nichols and Reaves (1958) pointed out that the angle of the tine of

subsoilers was important and reported that designers of subsoilers believed that there was a material reduction in draft for angles in the vicinity of 15 degrees. Additional work on the influence of factors affecting draft were published by Payne (1956) and Tanner (1960). For tine widths of 50, 75 and 100 mm, O'Callaghan and Farrelly (1964) found that draft increased with depth of tillage in the range of 50-100 mm, although for shallow depths (less than 50 mm) the results were inconclusive. Tanner (1960) also found that the direction of the vertical force was downward when the lift angle was 20 degrees, but had an upward component when the lift angle was greater than 60-75 degrees.

There has been considerable interest in developing mathematical models for the soil conditions from which forces on cultivation tools can be deduced. A recent paper by McKyes and Ali (1977) proposed a three-dimensional model for simple tools and obtained good correlation between the predicted draft for a swept blade and field data.

The manner in which speed influences the draft has also received considerable attention in the literature. McKibben and Reed (1952) reported that the effect of speed on draft was also influenced by the clay and moisture content as well as the kind of tillage tool in use. Rowe and Barnes (1961) suggested that draft could increase between 20 and 80% when the speed was doubled from 5 to 10 km/h. They believed this to be the result of the fact that at higher speeds the shear strength of the soil increased with higher rates of shear, but that the increase was not as great with soils having a high clay content. In the speed range of 4.8-9.6 km/h, Payne (1956) found the draft to increase by 11-16% for flat-plate tines whereas for sweep shovels in loam soils, Reed (1966) found the draft increased 4-13% for the

same speed range. McKibben and Reed (1952) also found, for the same speed range, the draft to increase by 16%. Stafford (1979) showed that the relationship between draft and speed was affected by moisture content and the nature of the soil failure, but for speeds in excess of 18 km/h draft was independent of speed.

A set of equations predicting the draft force of chisel plows and field cultivators has been published by the American Society of Agricultural Engineers (ASAE) (1980). The draft force was represented as a linear function of speed and a second degree polynomial function of depth. No mention was given to vertical or lateral forces or the effect that overlap might have on the applied loads to a cultivator sweep situated behind the front row of a cultivator assembly.

The objectives of this investigation were to measure the forces of cultivation for cultivator sweeps and spikes under a variety of depth and speed conditions in dry hard soils and to discover to what extent lateral and vertical forces are significant with respect to the draft forces. Additionally, the distribution of loads between a leading and trailing sweep with overlapping wings and frequency response of a sweep-shank were to be evaluated. By meeting these objectives it was hoped to confirm existing data or establish new data for the prediction of the loads of cultivation on sweep and spike cultivators. It is believed that these data will be of value to both designers and manufacturers of cultivator implements.

## EXPERIMENTAL PROGRAM

### Description of Apparatus

A mobile test frame was designed and constructed to carry a cultivator shank and holder assembly and fit onto a three-point hitch of a farm tractor (Bellow et al. 1980; Harrison 1974). This enabled the



cultivator assembly to be centrally attached to an active frame which was isolated from a passive frame by six load cells. A general schematic of the load frame showing the forces that were measured is shown in Fig. 1. Each load cell consisted of four electrical resistance strain gauges mounted on an aluminum rod forming a four-arm Wheatstone bridge circuit. In order to calculate the stress imposed on a cultivator shank, as well as serving as a check on the load cells, two electrical resistance strain gauges were mounted on the inside radius of the cultivator shank.

Depth of cultivation was selected by adjustment of gauge wheels in relation to the passive frame. Speed was monitored by a DC generator attached to one of the gauge wheels. To evaluate the interaction between trailing and leading sweeps a duplicate uninstrumented cultivator sweep assembly was mounted to the passive frame 400 mm in front of and 300 mm to the right of the instrumented trailing sweep. This caused a 25% overlap in sweeps (100 mm). A tandem arrangement of spikes was not tested as no overlap occurred in this case. Cultivator sweeps 406 mm wide and 51-mm-wide spikes were used for all field trials. The spring release mechanism incorporated in the design of the cultivator assembly tested was modified so that tripping-out was prevented enabling large loads to be applied and to maintain the sweep or spike at a

reasonably constant depth. From laboratory experiments it was found that for loads up to 9 kN the depth did not change by more than 10 mm. However, the cultivator shank was less stiff in the horizontal direction and for the same load range was found to deflect up to 100 mm. This would increase the rake angle of the sweep or spike, but was not believed to affect it significantly. The unloaded rake angle for the sweep was about 20 degrees and for the spike was about 17 degrees.

The force, strain and speed signals were transmitted from the tractor via a 30-m umbilical cord to a recording van housing signal conditioners, an FM tape recorder and an ultraviolet (UV) chart recorder. A general view of a typical test in progress is shown in Fig. 2.

### Testing Procedure

Moisture content and dry bulk density of the soil were measured at each test site using a gamma radiation source and detector. Measurements were taken at 25-mm intervals from the soil surface down to the deepest cultivation depth achieved. Except for the Ellerslie test site (no. 5) the field conditions were judged to be dry and hard packed. In this study only the percent moisture, percentage clay sand loam and density were used to characterize the soil conditions.

A test run consisted of accelerating the tractor to a selected speed, lowering the tool to engage the soil to a pre-set depth

and travelling the distance permitted by the umbilical cord (approximately 50 m). Recording of data took place throughout the entire sequence. Three, approximately equally spaced speeds between 6 and 12 km/h were selected for each depth using the sweeps. A single speed of 9 km/h was used for the spike. A shear pin in the active frame was designed to fail at a load of 13 kN to protect the load cells. In some situations this pin failed before maximum depth of cultivation was achieved.

At each test site three different cultivator systems were evaluated; single instrumented sweep, single instrumented spike and dual sweeps with trailing sweep instrumented. As the test run proceeded the outputs from the load cells were monitored visually on the UV recorder. If conditions did not appear satisfactory a second or third run at the same depth and speed were performed. Each test run was approximately 50 m and this generally served as an ample length from which repetitive data could be analyzed.

### DATA ANALYSIS

The analog data tape recordings were digitized at a rate of 167 times per second. This rate was chosen after a number of runs had been analyzed on a fast fourier transform (FFT) analyzer that showed that most of the output signals were contained in the DC to 55 Hz bandwidth. Digital FFT spectral analysis prescribes that a sampling rate be used which is at least twice the highest frequency expected.

A number of analytical procedures were programmed into a computer so that the digitized data could be analyzed directly for the mean and standard deviation of each load cell from which the draft, vertical and lateral forces were computed. Although the software for this was assembled without difficulty, considerable care had to be taken to select those portions of test runs for which the apparatus was considered to be operating under constant conditions of depth and speed. This was achieved by reviewing a computer-generated plot of the digitized load cell outputs along with the speed recordings on a CRT screen so that regions could be defined where the data analysis was to be performed.

The three forces on the tool were plotted against depth and speed and either linear, geometric (power), exponential or polynomial curves were fitted and correlated to the data.

### RESULTS AND OBSERVATIONS

#### Soil Classification

The soil textural classification for five sites tested is plotted in Fig. 3, according

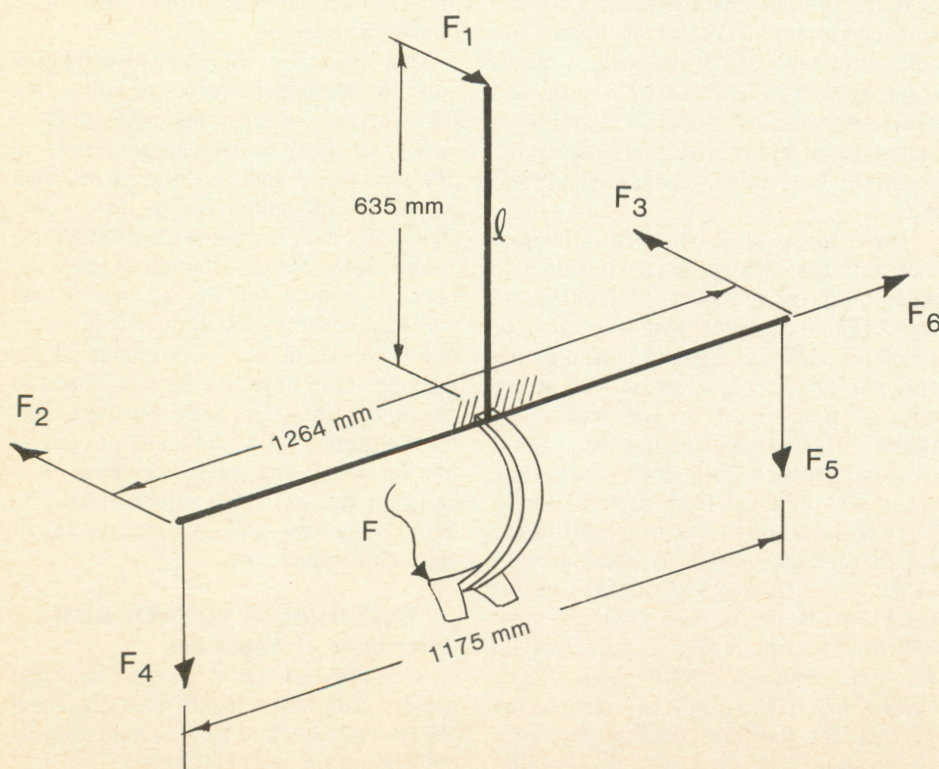


Figure 1. Load frame showing load cell locations and sweep location.



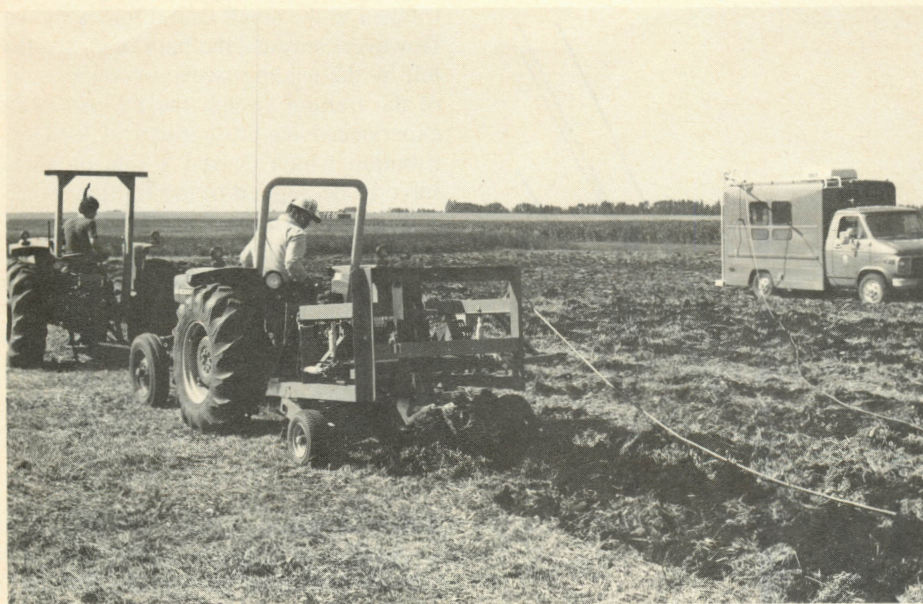


Figure 2. Test underway.

to the U.S. Department of Agriculture classification system. The results are an average of several core samples taken down to the deepest cultivation depth achieved.

With the exception of site no. 5, each site was considered a severe test for any tillage tool. Site no. 4 was a summer-fallow field, but all the others were stubble fields. Except for site no. 5 which was a silty-clay-loam soil, all soils fell into the

clay-loam category. It is seen from Fig. 3 that there was a small variation in clay content between all sites.

Table I shows the average dry density and moisture content measured at each test site. Again, excepting site no. 5, variation of dry density was less than 6% and moisture content varied less than 25% among the other four test sites.

Although an attempt was made to select locations of differing soil characteristics

TABLE I. MOISTURE AND DENSITY AT TEST SITES

Test site	Locality (Alberta)	Moisture content	Dry density (kg/m <sup>3</sup> )
1	Claresholm	11.2	1438
2	Lethbridge	9.6	1371
3	Coaldale	10.1	1386
4	Vegreville	14.1	1507
5	Ellerslie	48.9	907

(all in a dry moisture condition), it was observed that four were of a similar nature and only site no. 5 was noticeably different. It was therefore decided to plot results from all sites together, noting any anomalies caused by inclusion of the data from site no. 5.

### Effect of Depth

The results of each test run were analyzed as forces vs. depth and forces vs. speed. These results are plotted typically, as shown in Fig. 4. Figure 4 shows that the draft force increased with depth for a leading sweep, a trailing sweep and a spike. The solid lines are fitted polynomial curves computed by a least squares regression of force on depth. Inclusion of a linear term was neglected as it only increased the correlation in the order of 1% for all cases and was not considered significant.

Draft forces for a leading and trailing sweep and for a spike are plotted as points in Fig. 4. The solid lines are "best fit" polynomials through these points with the generated equation for each particular curve shown. The degree of correlation between the curves and the experimental data is shown in brackets. The dotted curves represent the theoretical prediction as proposed by the American Society of Agriculture Engineers (1980) for chisel plows and field cultivators in firm clay-loam soil. A speed of 9 km/h was used for the ASAE curves. It should be noted that the ASAE data give equations for force per tool including rolling resistance and were based on the draft forces measured at the hitch divided by the number of tools being used. As a result, the ASAE data do not discriminate between the draft force of a leading versus a trailing sweep nor do they separate the draft of a spike from that of a sweep.

Comparing the experimental results to the ASAE equation it can be seen that the ASAE curve predicts a draft force 10% lower for a leading sweep, 19% higher for a trailing sweep and 26% higher for a spike. For comparison, the data for the trailing and leading sweeps were averaged and plotted as the second dashed line in Fig. 4. As might be expected, on the basis

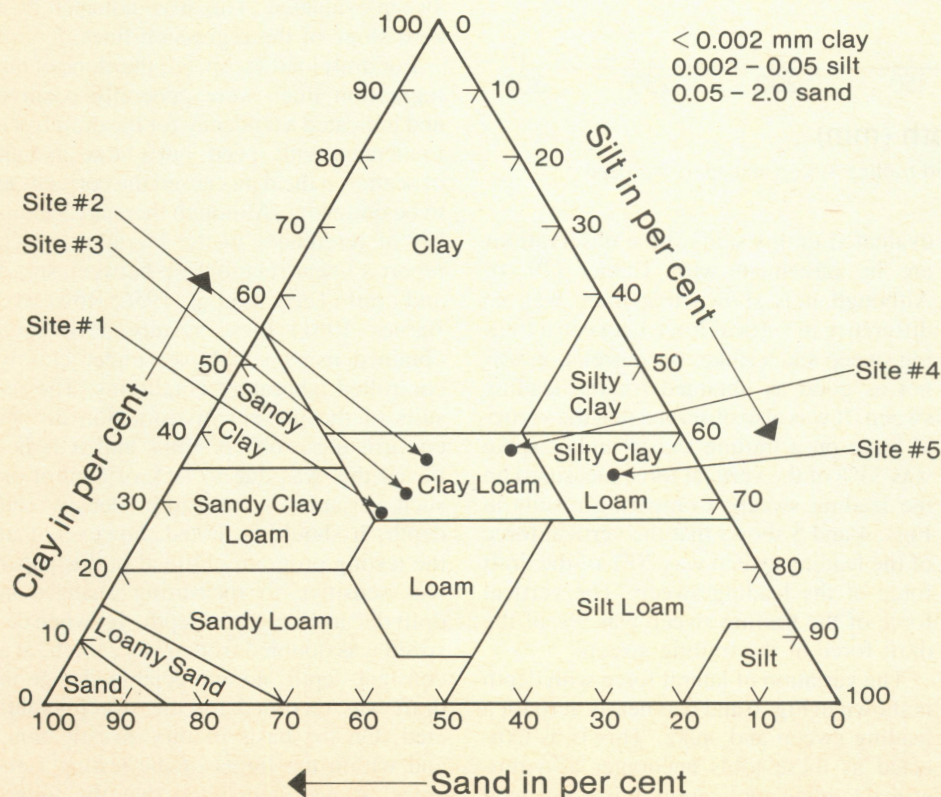


Figure 3. Soil classifications.



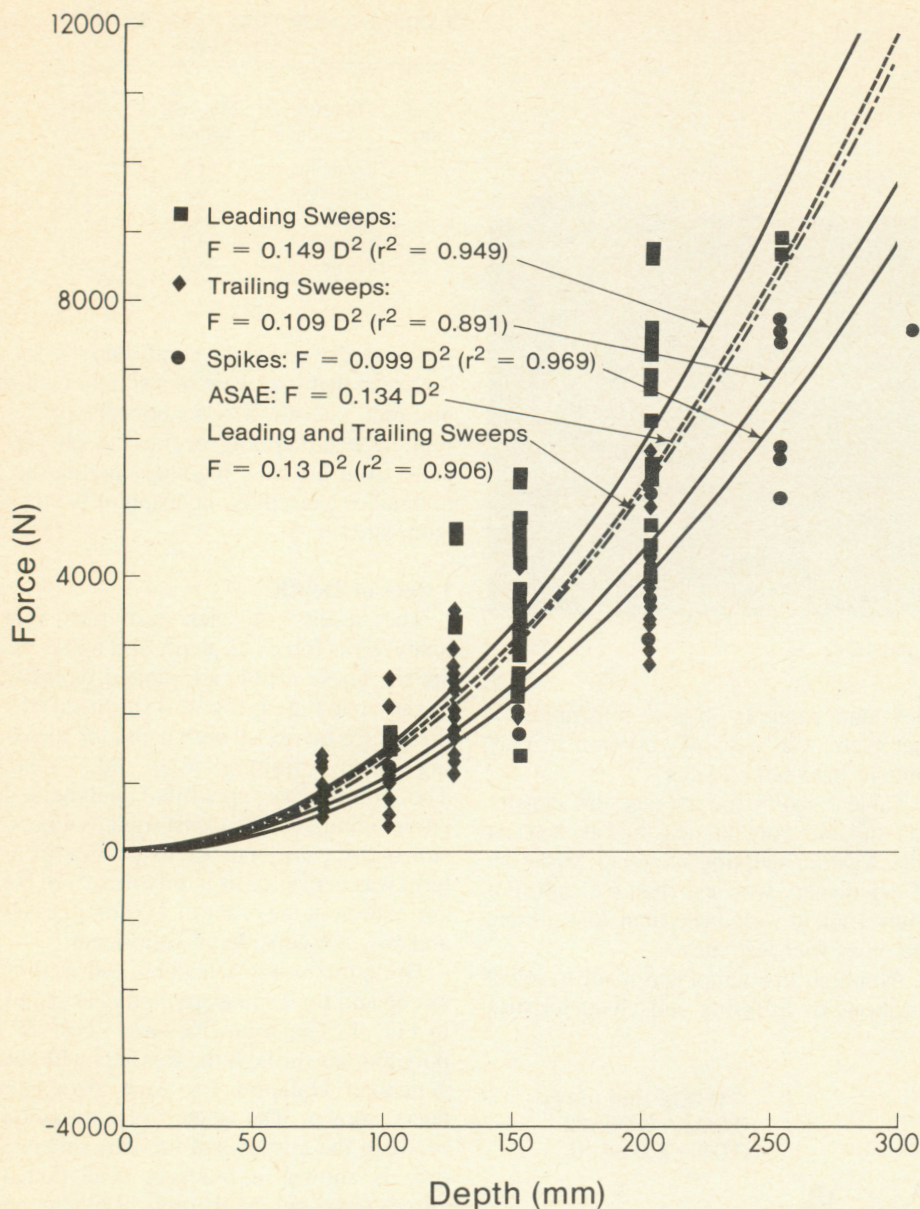


Figure 4. Draft forces for leading and trailing sweep and spike vs. depth.

of the average data, the results were very close to that predicted by the ASAE formula, within 3%, although the correlation was somewhat poorer. A final observation was made by comparing the curves for leading and trailing sweeps where it was noted that the draft force on the trailing sweep was 27% less than that measured on the leading sweep. Also, a comparison between the sweep and spike tested showed the draft on the spike to be 34% less than that on the leading sweep.

The variation of vertical force with depth is shown in Fig. 5 and is seen to increase downward with depth for a leading sweep and spike. Upward vertical forces can be produced on a trailing sweep at shallow depths and were observed during the course of this investigation, but usually the vertical force was directed downwards. For the rake angle of the tools

evaluated in this study these observations are in agreement with Tanner (1960). Although it is shown that there was no difference in vertical force between a trailing sweep and a spike, the correlation was not as good as obtained for the leading sweep. It was also observed that the vertical force on a trailing sweep and/or spike was 34% of the vertical force measured on the leading sweep. Comparing results in Figs. 4 and 5 shows that the vertical force of the leading sweep was 20% of the draft force of the leading sweep. The vertical force of the trailing sweep was 9% of the draft force of the trailing sweep.

The variation of lateral force with depth is shown in Fig. 6 and was nearly zero for a leading sweep and spike. This is as expected as these tools encounter a symmetrical loading application. It was assumed that misalignment of the active frame con-

tributed to the small lateral forces shown. However, because the path of cultivation left by the leading sweep overlapped that of the trailing sweep, the trailing sweep experienced an unsymmetrical load distribution which caused a side or lateral force to be applied to the trailing sweep. This lateral force has been generally neglected by other investigators, but the data plotted in Fig. 6 show that the lateral force of the trailing sweep increased with depth and was measured to be 20% of the draft of the trailing sweep. This factor is important and should be included when considering a stress analysis of a cultivator shank and holder assembly.

### Effect of Speed

Another objective of this investigation was to determine the nature of the relationship between speed and force on a cultivator sweep. However, variation of tractor speed was restricted to the practical range of speeds at which a farmer might operate his machinery. The draft, vertical and lateral forces were plotted against forward speed for the leading and trailing sweep for each depth tested and linear regression curves were fitted to the data. Although not shown here, it was found that the effect of forward speed was less pronounced than the effect of depth of tillage. In fact there was little, if any, correlation observed between either the vertical or lateral force with speed for the sweep evaluated. This was indicated by a zero slope of the regression lines.

For draft load vs. speed, the slope of the regression lines were generally positive and indicated a tendency for the draft force to increase with speed, but a large amount of scatter in the data caused the correlation to be quite low. Although there are a number of references in the literature which report a linear relationship between speed and draft (Telischi et al. 1956; Rowe and Barnes 1961) these results have been obtained using soil boxes under closely controlled laboratory conditions. The results of the present investigation do not confirm these observations and it is believed this was due to lack of control on such variables as moisture, density and depth. It should be noted, however, that the testing program outlined in this paper was sensitive to measuring changes in draft due to changes in depth, yet when the speed was doubled from 6 to 12 km/h, at a constant depth, no appreciable change in draft was recorded for the sweep evaluated. On the basis of this investigation, and within the limits of the testing variables, it was concluded that the forces acting on sweeps under actual tillage con-



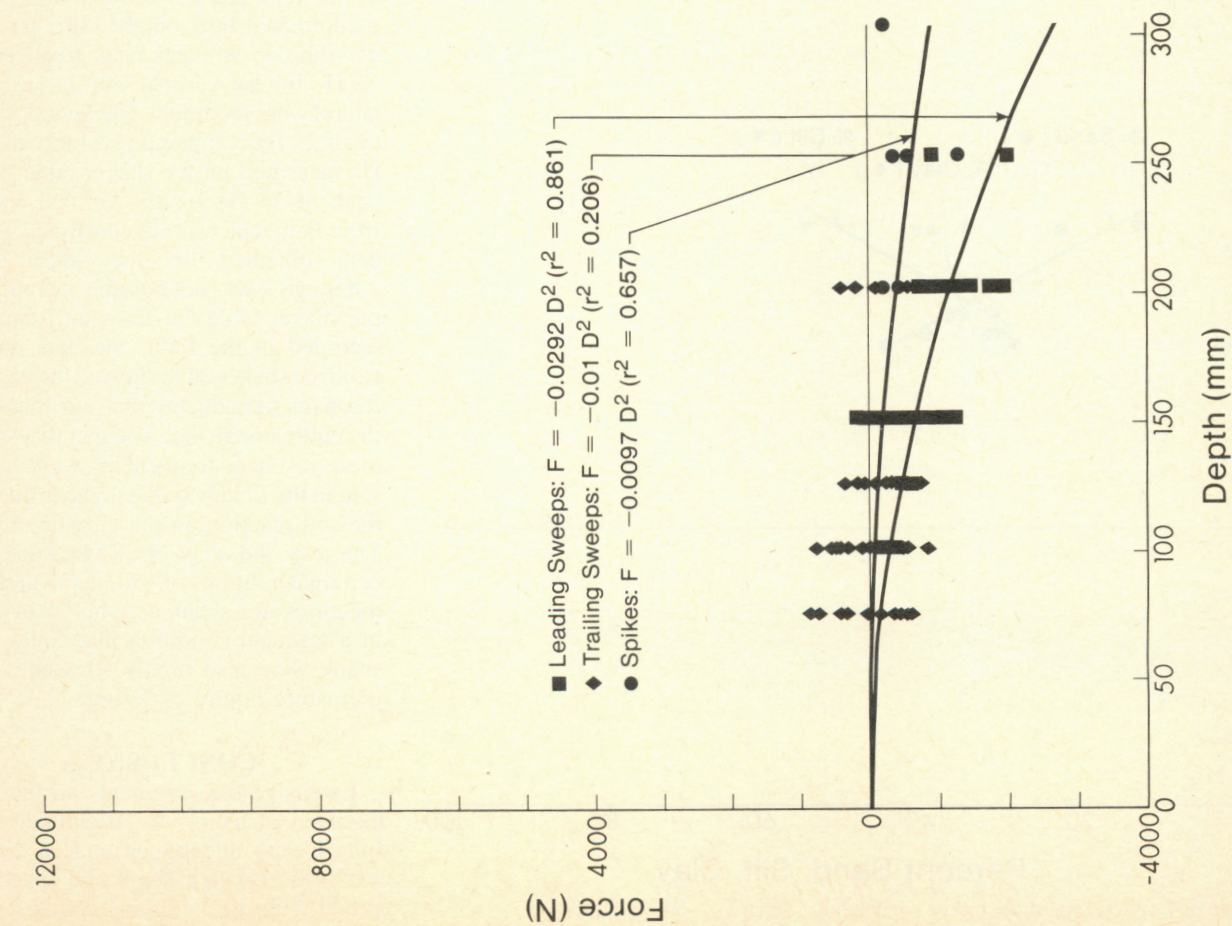


Figure 5. Vertical forces for leading and trailing sweep and spike vs. depth.

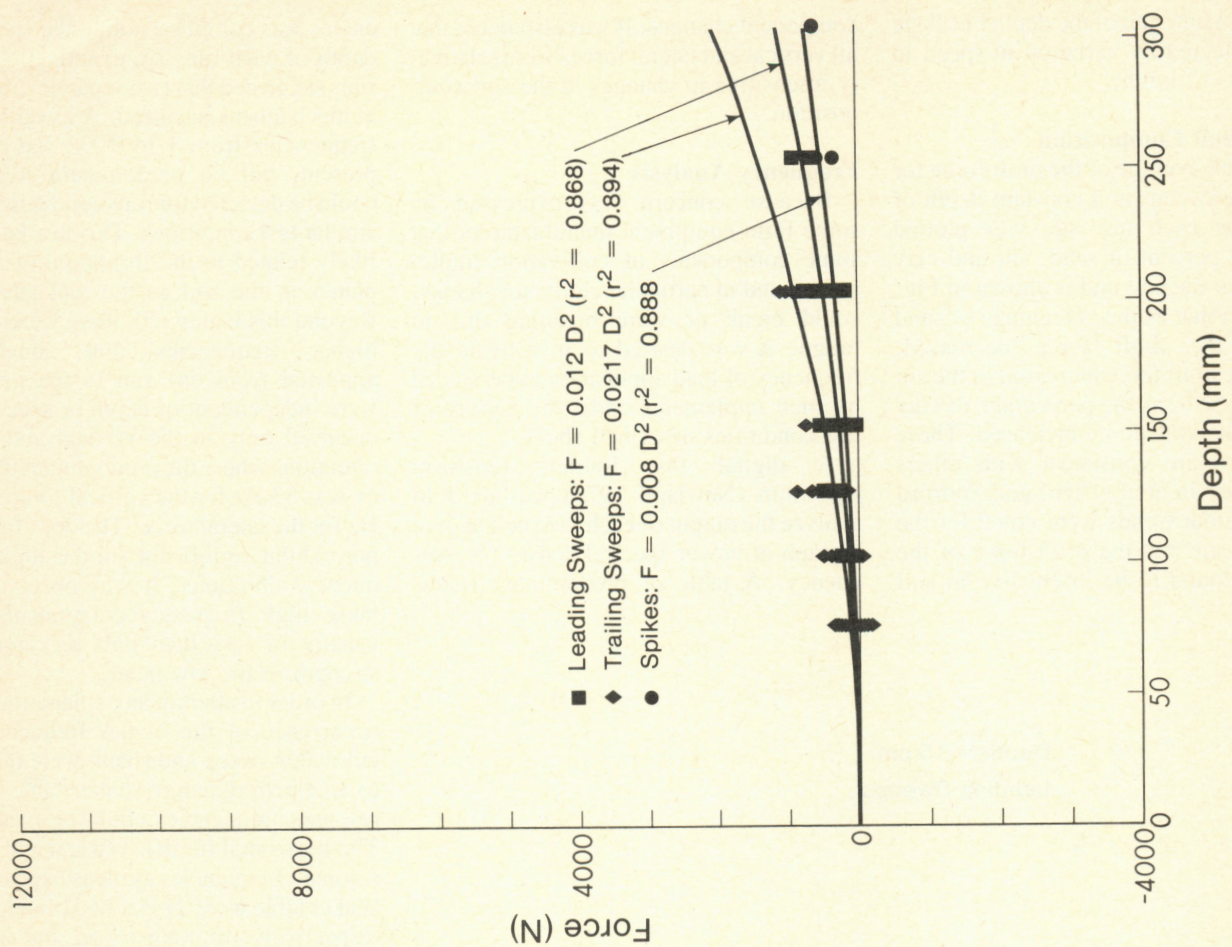


Figure 6. Lateral forces for leading and trailing sweep and spike vs. depth.



ditions are a function of the depth of tillage and not affected by variation in speed in the range 6-12 km/h.

### Effect of Soil Composition

An overall average of the draft force for the leading sweeps at a constant depth of 150 mm at each test site was plotted against the percent of sand, silt and clay contained in the soil and is shown in Fig. 7. It is seen that as the percentage of sand increased the draft force decreased, whereas the draft force increased as the silt increased. Also, as the percentage of clay increased the draft force increased. These observations are consistent with others such as Telischi et al (1956) and Stafford (1979). Similar trends were noted for the trailing sweep, but the draft force of the spike was found to be insensitive to soil

component changes. It was also noted that all vertical and lateral forces were relatively insensitive to changes in the soil composition.

### Frequency Analysis

Because concern was expressed by some farm equipment manufacturers that some components of cultivation implements, and in particular cultivator shanks, could break or were breaking due to fatigue it was desired to investigate the frequency of load application experienced by such implements under the variety of test conditions described above.

A digital fast fourier transform algorithm (Newland 1975) was used to analyze the output of each load cell to give a graph of power spectral density vs. frequency. A table of predominant frequ-

encies was compiled noting the speed and depth of each run. An examination of all runs suggested that two separate vibrational mechanisms occurred. A lower band of frequencies from 1 to 9 Hz was usually present, but no predominant frequency could be detected for runs conducted under similar test conditions. This low band was likely related to the formation of rupture planes in the soil as the tool advanced. Beyond this bandwidth there were certain higher frequencies that consistently appeared from one run to the next and were independent of depth or speed. This occurred only in the vertical and lateral directions where the predominant frequency was 33 Hz for the vertical force and 24 Hz for the lateral force. The draft force did not exhibit significant similar higher frequency vibrations. It was observed that these high frequency components were usually of less than half the amplitude strength of the low band.

In order to attempt an explanation of the occurrence of the higher frequencies, a cultivator sweep and shank were mounted to an electrodynamic shaker table so that resonant frequencies could be measured. The horizontal (draft), vertical and lateral resonant frequencies as measured from the shaker table were 21 Hz, 66 Hz and 26 Hz, respectively. In comparison, the analysis of the field data showed that there was no predominant horizontal (draft) frequency of vibration whereas peak frequencies at 33 Hz for the vertical and 24 Hz for the lateral were recorded. The lateral frequency of 24 Hz compared favorably to the 26 Hz measured on the shaker table, but the peak of 33 Hz for the vertical observed from field data was not confirmed with the data obtained on the shaker table. Although it was not possible to confirm on the shaker table the resonant frequencies recorded in the field, the data obtained from the shaker table showed the variety of resonant frequencies that are inherent in the cultivator shank. The fact that some of these resonant frequencies were not present in the field was due to the influence of the soil reaction on the vibrating system. The tests did show, however, that under certain conditions of soil, depth and speed the cultivator shank assembly can vibrate in a resonant condition that could, if the shank were also highly stressed, lead to premature failure by fatigue.

### CONCLUSIONS

Extensive measurements on the forces involved in using sweep cultivators and spikes were undertaken at five different test sites at which depth and speed were varied with the following conclusions.

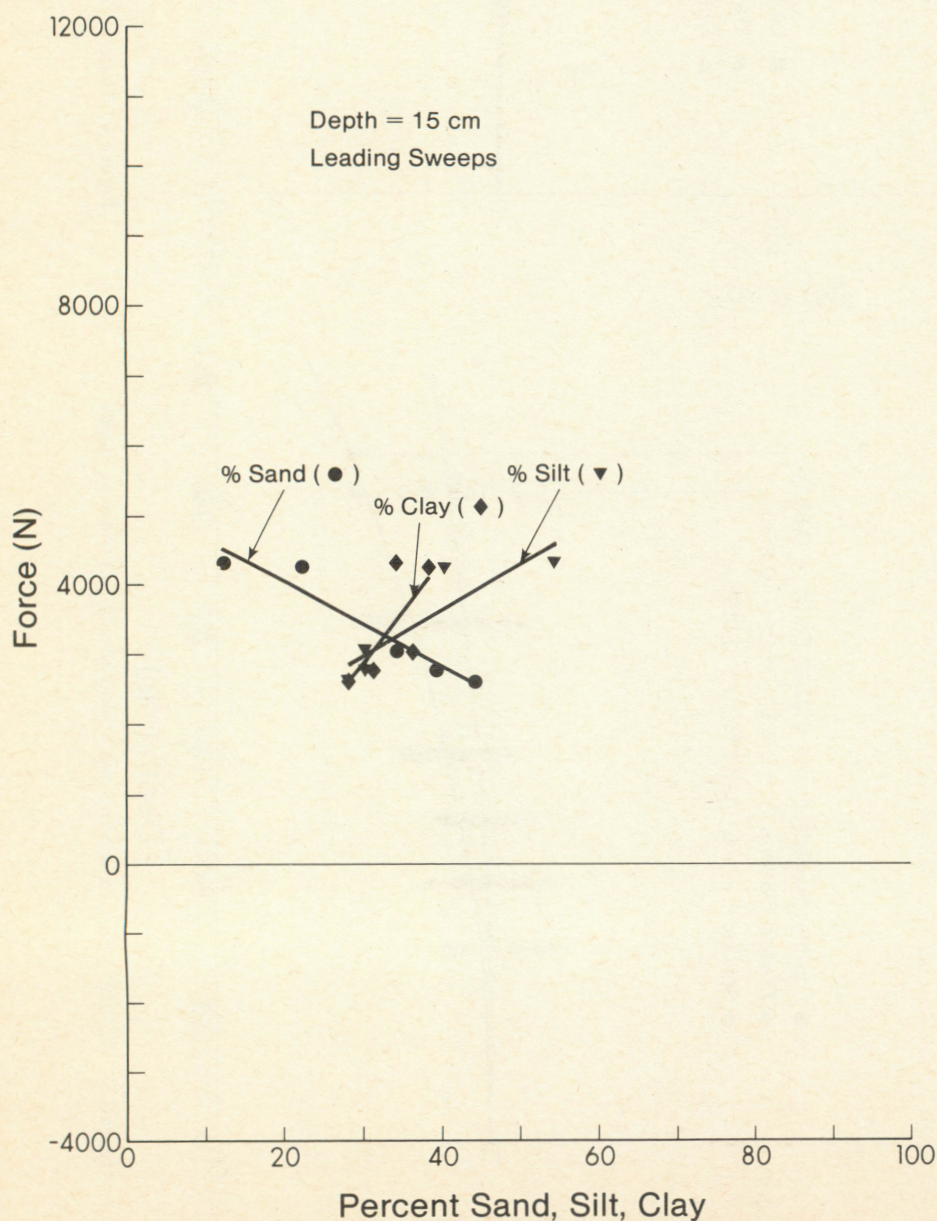


Figure 7. Average draft forces for leading sweep vs. soil classification.



1. Draft force increased with depth of cultivation and could be approximated with an equation similar to that published by the American Society of Agricultural Engineers. Additional regression analysis is given to show the load distribution between leading and trailing sweeps and spikes.

2. The draft force of a trailing sweep was approximately 27% less than measured on the leading (and overlapping) sweep and the draft force of a spike was approximately 34% less than the draft force of a leading sweep.

3. Lateral and vertical forces were measured up to 20% of the draft force. However, lateral forces were generally small or non-existent for leading sweeps and spikes.

4. Tool forces did not appear to be affected by speed in the range 6-12 km/h for the cultivator sweep evaluated.

5. Predominant frequencies of vibration of the implements tested were observed in the range 1 to 9 Hz, although some peaks were noted at higher frequencies.

## ACKNOWLEDGMENTS

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