Operating speed effect on the advancing soil failure zone in tillage operation

Z.X. ZHANG and R.L. KUSHWAHA

Department of Agricultural & Bioresource Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK, Canada S7N 5A9. *Received 12 September 1998; accepted 23 April 1999.*

Zhang, Z.X. and Kushwaha, R.L. 1999. **Operating speed effect on the advancing soil failure zone in tillage operation**. Can. Agric. Eng. **41**:087-092. A series of experiments were conducted in the soil bin for investigation of the assumption that the advance of the soil failure zone and the energy requirement for manipulation of the soil in tillage operations will reduce if operating speed is greater than a critical speed. Several flexible sensors (piezo films) were embedded into soil in the direction of tool travel to measure soil deformation during tillage operations. The soil failure zone in front of the tool was determined by the measurement of the distance from the tool to the point at which the soil began to deform. The preliminary test results indicated that the operating speed effect on the advancing speed of soil failure at different soil moistures, soil compactions, and tool shapes could be evaluated by this technique. As a result, the critical speed can be calculated for the given soil conditions and tool shapes.

Une série d'expériences ont été effectuées dans un bac de sol pour vérifier l'hypothèse que la zone de déformation du sol ainsi que l'énergie requise dans la manipulation d'un outil de labour diminuaient si la vitesse d'opération dépassait une certaine valeur critique. Plusieurs détecteurs piézo-électriques flexibles (film) ont été mis dans le sol dans la direction du labour pour mesurer la déformation du sol durant le labour. La zone de déformation du sol en avant de l'outil a été déterminée en mesurant la distance de l'outil jusqu'au point où le sol commence à se déformer. Les résultats préliminaires indiquent que la vitesse d'opération de l'outil par rapport à la vitesse de déformation du sol pour différents taux d'humidité et de compaction des sols ainsi que pour différentes formes d'outils de labour peut être évalué par cette méthode. Ainsi, la vitesse critique peut être calculée pour n'importe quelle condition de sol ainsi que pour différentes formes d'outil de labour.

INTRODUCTION

A tillage operation is basically a dynamic process. The draft and energy requirements are dependent on operating speed. There are three mechanisms accounting for the draft increase with increase in operating speed: 1) soil inertial effect, 2) soil strength rate effect, and 3) wave propagation effect.

The soil inertial effect on draft was first considered by Goryachkin (1929), who proposed that the draft for a tractor plow was directly proportional to the square of the speed. With the preliminary assumption of soil failure as a wedge, the inertial component of draft could be predicted mathematically (Soehne 1956). However, Siemens et al. (1965) found that the calculated draft according to the soil acceleration was less than the measured value and their test data could be described with a quadratic form of speed. This fact suggested that some factors other than acceleration dominated the increase in draft with speed. Wismer and Luth (1972) found that the characteristics of draft variation with speed were connected with soil classes. For air dry sand, a pure frictional soil, the increase in draft was accounted for by the inertial effect up to the speed of 2.54 m/s. For a cohesive-frictional soil, say loam, only a part of the draft increase was accounted for by soil acceleration, while for clay the increasing rate of draft reduced with an increase in speed. The rate dependency of soil strength was believed to govern the draft response with speed for clay.

A similar investigation was also conducted by Stafford (1979, 1984), who pointed out that the soil failure profile was not only associated with various soil types, but also with soil moisture and operating speed. For dryer soils, soil failure was defined by the Mohr-Coulomb criterion and the curves of draft vs speed exhibited a concave form, i.e., the rate of increase in draft increased with speed. This behavior of draft vs speed can be described in terms of soil inertia forces. However, for wet soils, the soil failure pattern appeared to be a continuous flow. Correspondingly, the draft vs speed curves exhibited a convex shape, i.e., the rate of incrase in draft reduced with speed. At high speed, soil underwent plastic failure for both dry and wet soils. The successive experiments (Stafford and Tanner 1983a, 1983b; Zeng and Yao 1991) showed that soil shear strength followed the Mohr-Coulomb equation, but soil cohesion increased with increasing speed.

In addition to the above investigations, Russian researchers made a series of extensive theoretical investigations on tool draft at the high operating speed (Azyamova 1963; Katsygin 1969a, 1969b; Vetrov and Stanevski 1972). The main point of the proposed theory was that the change in draft response to the operating speed was associated with the wave propagation of soil stress. This idea was based on the recognition that the deformation distributed in soil media was not instantaneous, but required a little time. An extensive soil stress or energy concentration occurred in front of the tool when the tool speed was less than the velocity of the wave propagation of soil stress. With an increase in tool speed, the stress concentration was increased, such that the soil cutting force was consequently increased. As the tool speed increased faster than the wave of soil stress propagation, theoretically the plastic zone of soil in front of the tools decreased or even disappeared, thus the soil cutting resistance would decrease. Accordingly, there was an optimal operating speed at which the performance in tillage operations would result in lower draft. If this theory holds true, it has a great potential significance for optimizing the design of soil engaging tools. Therefore, the theory attracted some researchers' interests (Hendrick and Gill 1973; Kushwaha and Linke 1996). However, there aren't any test data that could

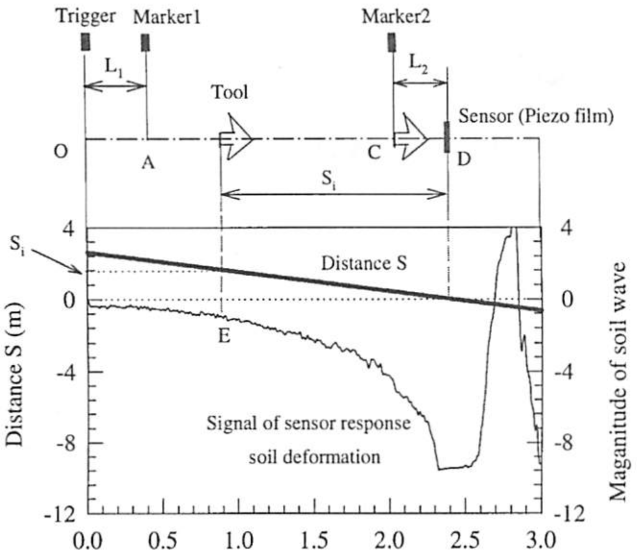


Fig. 1. Schematic for measuring soil deformation zone. S = distance of tool from sensor; E = point that a sensor has a distinct response to soil deformation.

verify whether the theory is valid or not. This paper is to investigate further the reality of applying the theory in tillage operations. For this purpose, an approach to evaluate the operating speed effect on the soil deformation zone in tillage operations was developed.

SCHEME FOR EVALUATION OF THE SOIL DEFORMATION ZONE

The soil in front of a tool deforms as it is subjected to a load during tillage operations. The extent of soil deformation or strain will decrease with the increase in the distance away from the tool, so that a soil deformation zone in front of the tool is formed with respect to the tool. However, if a point in front of a moving tool is taken as a reference, the strain of soil deformation induced by a moving tool will increase from zero to a peak as the tool approaches the point. The effective distance is from the tool to the reference point in the soil at which the soil deformation just started to occur. This distance can be used for the evaluation of the domain of soil deformation.

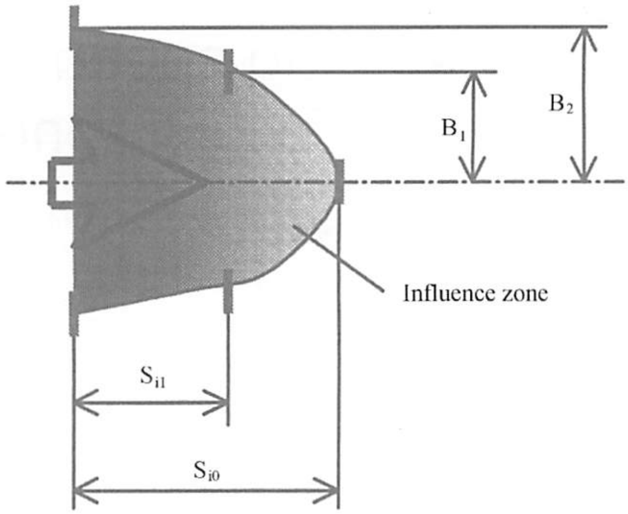
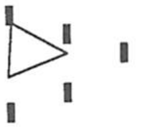
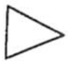


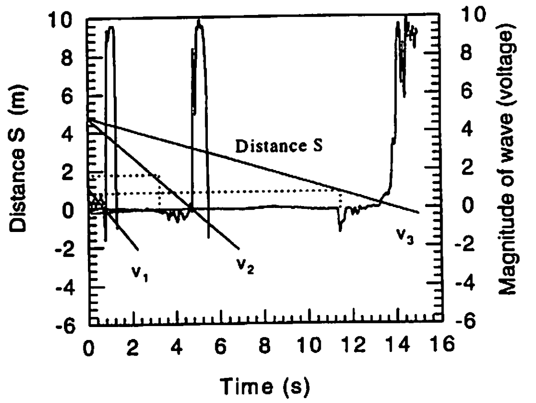
Fig. 2. Definition of influence zone.

This idea can be implemented using the test procedure illustrated in Fig. 1. A sensor (piezo film) was embedded into the soil at point D. Two markers were designed for measurement of operating speed and determination of the position where the sensor was buried in the soil. Marker1 was fixed, with a distance 1.2 m from the trigger, but marker2 could be moved according to the position of the sensor.

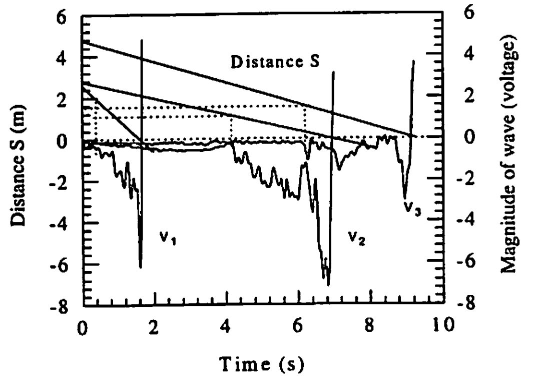
Suppose a tool is moving at a speed V. According to Fig. 1, the distance of tool from the sensor, S, at any time can be

Table I. Summary of test conditions.

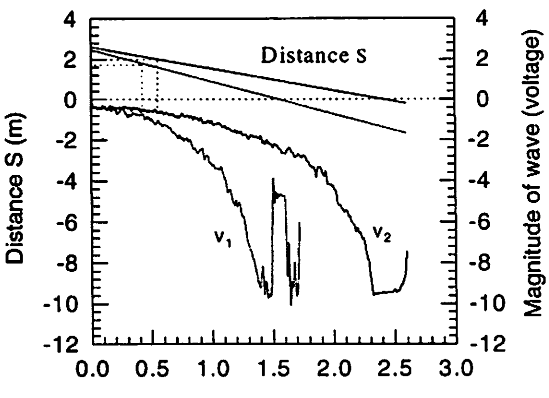
	triangular pattern	line pattern	
Alignment of piezo film			
	straight sweep	wide flat	vertical flat
Tool types			
Tool motion manner	smooth	sudden stop	
Soil moisture content (%)	13.4	15.7	
Soil compaction	low	medium	
Tillage depth (mm)	50	80	



(a) **Sweep tool with smooth movement manner. Moisture content = 13.4%; tillage depth = 50 mm; low soil compaction; V_1 = 1.43 m/s; V_2 = 1.01 m/s; V_3 = 0.34 m/s.**



(b) **Sweep tool with smooth movement manner. Moisture content = 13.4%; tillage depth = 50 mm; medium soil compaction; V_1 = 1.61 m/s; V_2 = 0.40 m/s; V_3 = 0.52 m/s.**



(c) **Sweep tool with sudden movement manner. Moisture content = 15.4%; tillage depth = 80 mm; low soil compaction; V_1 = 1.60 m/s; V_2 = 1.08 m/s.**

Fig. 3. Typical piezo film response to soil deformation.

calculated as:

$$S = L_2 + \frac{n_2 - n}{n_1} L_1 \tag{1}$$

The operating speed is given as:

$$V = \frac{F_s L_1}{n_1} \tag{2}$$

where:

n_1, n_2 = number of sampling points at marker1 and marker 2, respectively,
n = number of sampling points at any time,
L_1 = distance from marker1 to trigger (1.2 m),
L_2 = distance from the sensor to marker2, and
F_s = frequency of sampling.

The relationship between the distance S and time in Eq. 1 is given as a heavy black line in Fig.1. At the same time, the signal measured by the sensor responding to the soil deformation is given as a curve in Fig. 1. Accordingly, we can determine the required distance S_i (Fig. 1) at which the sensor has a distinct response to soil deformation while the tool is moving. This distance S_i is referred as to the *influence distance* with respect to an operating speed. Evidently, the influence distance is related to the side distance of the sensor from the tool. As side distance increases, the influence distance will be decreased. For example, as shown in Fig. 2, the influence distance corresponding to the side distance B_1 is S_{i1} and it is zero for B_2. Accordingly, a zone is formed. This zone is referred as to as the *influence zone* and it is a function of operating speed. If the theory of wave propagation related to the mechanism of draft increase is valid, there must exist a critical speed after which the influence distance or the area of the influence zone will be decreased with increase in operating speed. Therefore, the critical speed can be determined according to a series of tests at different operating speeds.

EXPERIMENTATION

To examine the operating speed effect on both influence distance and influence zone, several experiments were carried out in an indoor soil bin of the Department of Agricultural and Bioresource Engineering, University of Saskatchewan. The soil bin was 1.75 m wide and 12.2 m long. The soil used in tests was identified as a clay loam composed of 47% sand, 24% silt, and 29% clay. The soil moisture content during tests varied from 13.4 % to 15.7%. Soil compaction was controlled at low and medium levels and measured with an impact penetrometer (Zhang and Kushwaha 1997).

After the soil in the bin was leveled and compacted, five piezo films were buried into the soil at 20 mm depth to detect soil deformation during the tillage operation. Piezo film is a flexible, lightweight, tough plastic film 70 mm long, 7 mm wide, and 53 μm thick. The advantages of piezo film are that it has a wide frequency range from 0.001 to 109 Hz, high sensitivity, and a low cost. The piezo films were aligned in the soil bin in two patterns as shown in Table I. A triangular pattern was used to measure the influence zone and a line pattern to detect the speed of the stress wave propagation. Three tools were used in the tests. A sweep, 300 mm wide, was oriented for normal operation, a wide flat tool, 150 mm in width, was

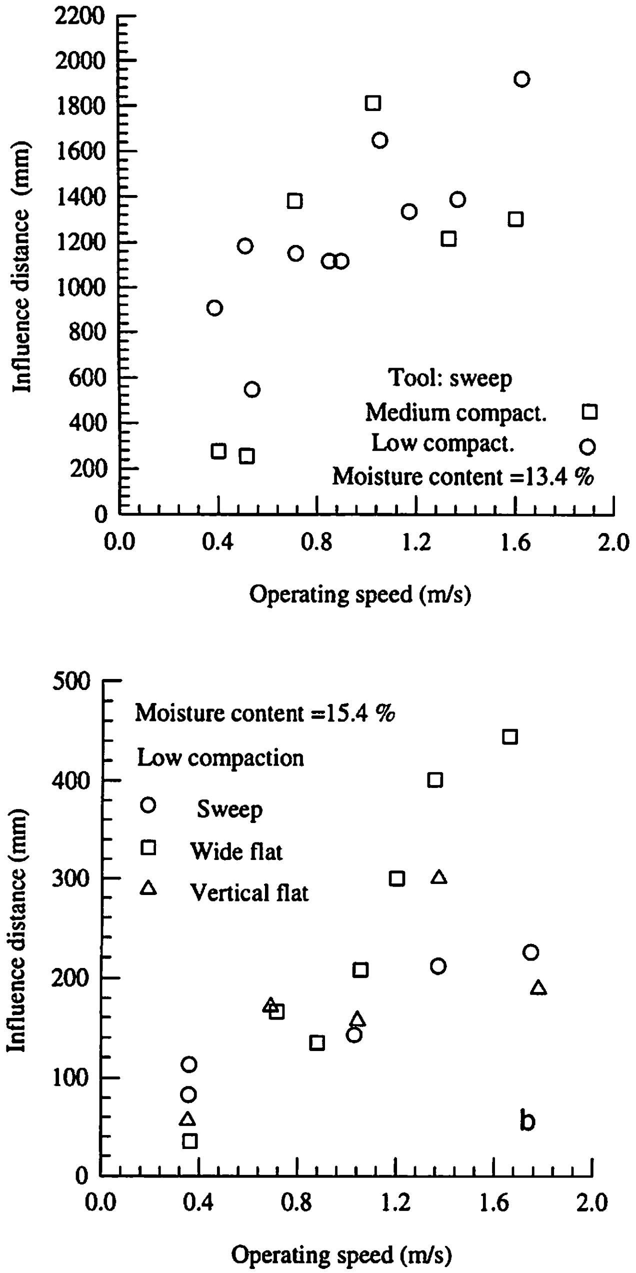


Fig. 4. Operating speed effect on the influence distance.

installed with a rake angle of 60°, and a vertical flat tool, 105 mm wide, was installed with a rake angle 90°. The tool motion during tests was conducted in two manners, smooth movement and a sudden stop. In the first case, the tool operation was performed at constant speed. In the second case, the tool first moved smoothly, but it was suddenly stopped as it approached marker 2 (Fig.1). The stop movement was applied to the line alignment of piezo film for the generation of a pulse load. The conditions used in tests are summarized in Table I.

RESULTS and DISCUSSIONS

Typical signals measured with piezo film during the test are illustrated in Fig. 3. In these figures, the straight lines are, S, the distance from the tool to the sensor for different operating

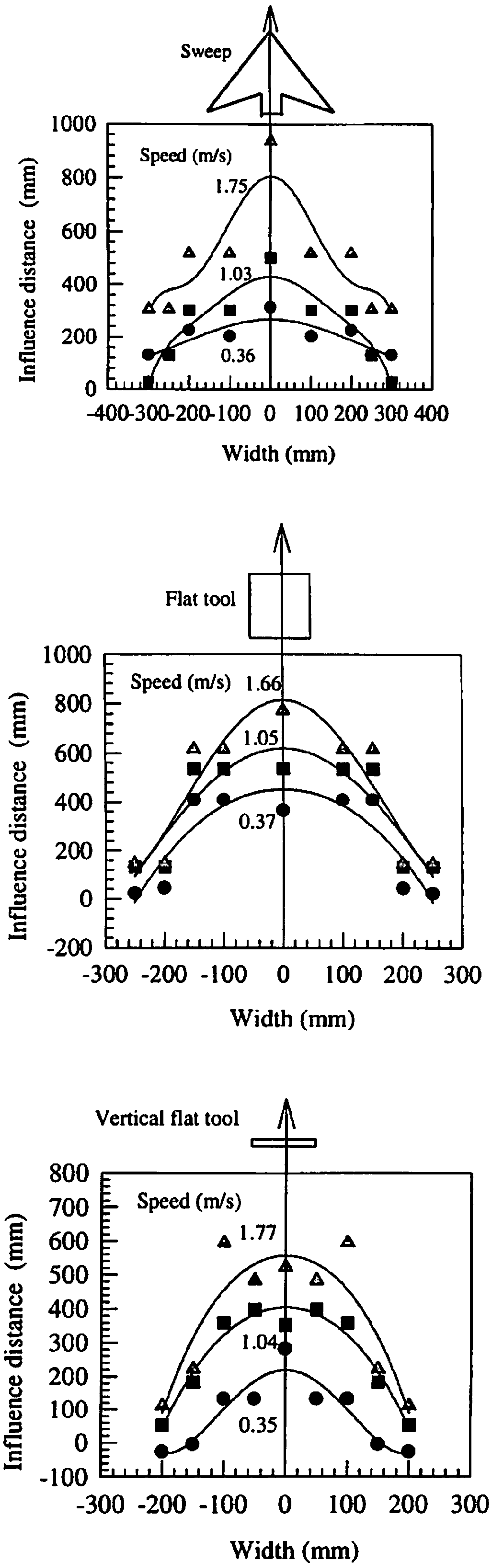


Fig. 5. Operating speed effect on the influence zone.

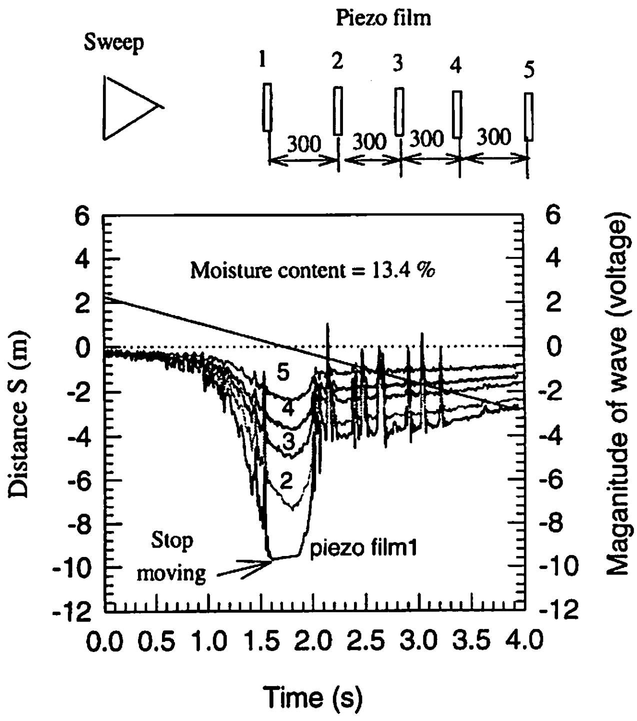


Fig. 6. Signal of soil deformation under pulse load.

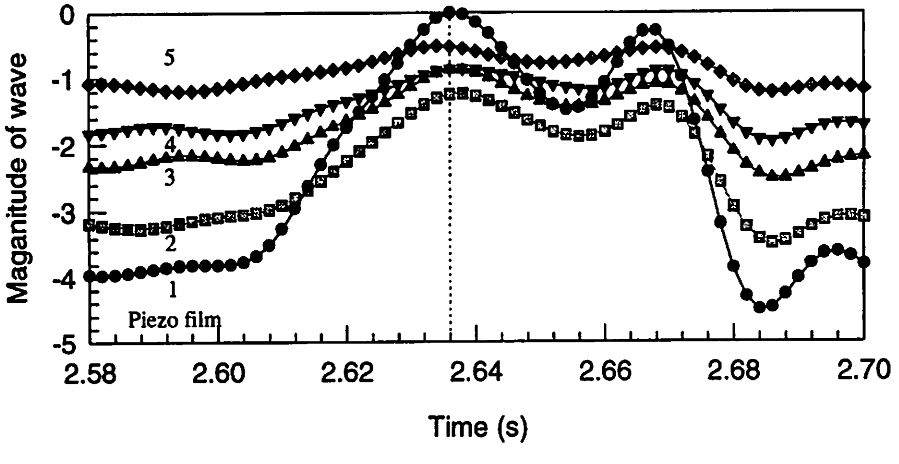


Fig. 7. Magnification of pulse signal for determining wave speed.

speeds v_1, v_2, and v_3. The influence distance is indicated by a dotted line in Fig.3. In the first test stage, the frequency of sampling was set as 80 points per second (Figs. 3a and 3b), but it was found to be too low to detect stress wave propagation. Therefore, in the second test stage (Fig. 3c), the frequency of sampling was increased to 500 points per seconds (or 0.002 second per sampling point), but it was still found that a faster frequency of sampling than this value was required to measure the speed of the stress wave propagation. Because the computer buffer was limited, the increase of frequency of sampling required a decrease in stay time of sampling. According to these figures, we can determine the time or the number of sampling points at which the piezo film just has an apparent response to soil deformation. The distance S is calculated in terms of Eq.1 for different operating speeds. Consequently, the relationship between the influence distance and speed is given in Fig. 4.

The data in Fig. 4 have some scatter resulting from errors in determination of the number of sampling points corresponding to the initial signal response to soil deformation and due to soil conditions not being identically uniform. But the results have shown that the influence distance increased rapidly with the increase in operating speed. A maximum influence distance of about 1920 mm was measured at speed of 1.63 m/s for low soil compaction (Fig 4a). In Figure 4b, where the soil condition is almost the same as the condition in Fig. 4a for low compaction soil, the influence distance for the sweep was only 225.5 mm at 1.75 m/s speed. It is not clear why the influence distance changed so greatly. In comparison, the wide flat tool resulted in a larger influence distance than the sweep and vertical flat tool.

The operating speed effect on the influence zone is shown in Fig. 5. It is apparent that the influence zone area increases with increase in operating speed. Also, the figure indicates that a larger influence zone was generated with the sweep since it is nearly three times the width for the other tools. Unfortunately, due to technical limitations of the soil bin, the behavior of the influence distance and zone with change in operating speed over 1.8 m/s has not been obtained. Consequently, we could not determine the critical speed over which both influence distance and zone slow down as the speed keeps increasing. However, if the wave propagation theory referenced earlier is true, the upper limit of the critical speed could be estimated with the speed of wave propagation. For this purpose, an extra test was performed at sampling frequency of 500 points per second. Five piezo films were embedded into the soil with a line alignment at intervals of 300 mm. During the tests, the tool was forced to a sudden stop when it approached the maker 2, giving soil an approximated pulse load. The signal measured by the piezo film in this test is illustrated in Fig. 6.

It can be seen from Fig. 6 that after stopping, some pulse signals were generated. These signals propagated freely from tool to the sensor. Therefore, it can be considered as stress wave propagation after applying a pulse load. The signal gathered from time 2.58 s to 2.78 s was magnified as shown in Fig.7. The figure shows that the waveform is similar for each signal. It was still difficult to measure wave speed from the data in Fig. 7, because the time interval of the wave peaks for two adjacent signals was too close to differentiate. But the estimation of the speed of the stress wave propagation of the soil in this test ranged from 40 to 150 m/s with average of 95 m/s. Kushwaha and Linke (1996) reported a wave propagation speed of 26 to 49 m/s for pressure waves calculated from soil test data. The analysis of their field test data showed the critical speed of 3 to 5 m/s for simple tillage tools. If the current data are an estimation of wave propagation speed and the theory holds that the optimum tillage operation occurs as operating speed approaches the speed of stress wave propagation, the critical operating speed will be very high for practical operations.

CONCLUSIONS

1. Piezo films were successfully employed to measure soil disturbance in tillage operations.
2. A method to investigate the operating speed effect on an advancing soil failure zone was developed. For this purpose, the influence distance and influence zone were defined. Consequently, the relationship between influence distance or influence zone vs operating speed can be established according to tillage operations at different speeds.
3. The results have indicated that with an increase in operating speed, the influence distance and influence zones were increased. But due to technical limitations of the soil bin, the critical speed was not reached.
4. The speed of stress wave propagation was estimated as approximately 95 m/s as an average. This value is very high for practical tillage operations, based on the speed of the stress wave propagation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from the Natural Science and Engineering Research Council of Canada. The authors also greatly appreciated the assistance from Louis Roth, Wayne Morley, and Karim Sharifat in preparation for experiments, data acquisition, and instrumentation.

REFFERENCES

Azyamova, E.N. 1963. Studies of dynamics of deformation of soil. *Trudy Minsk* 1:131-139. Translated by W.R. Gill, National Tillage Machinery Laboratory, Unites States Department of Agriculture, Auburn, AL.

Goryachkin, V.P. 1929. *Collected Works in Three Volumes*, vol. II, 2nd edition, ed. N.D. Luchinskii. Translated by Russian, Israel Program for Scientific Translations, Jerusalem, Israel.

Hendrick, J.G. and W. R. Gill, 1973. Soil reaction to high speed cutting. *Transactions of the ASAE* 16(3): 401-403.

Katsygin, V.V. 1969a. Investigation of the influence of increasing operating speeds of machines on the crumbling of soil and the expenditure of energy. *Voprosy Zwmledel'cheskoi Mekaniki* VII, Part 2, section 2, 49-59. Translated by W.R. Gill, National Tillage Machinery Laboratory, Auburn, AL.

Katsygin, V.V. 1969b. Relation of draft of agricultural machines to the operating speed. *Voprisy Sel'skohozyaistvennoi Mekhaniki* XIII. Minsk, USSR: Urozhai Publishing House. Translated by W. R. Gill. National Tillage Machinery Laboratory, Auburn, AL.

Kushwaha, R.L. and C. Linke. 1996. Draft-speed relationship of simple tillage tools at high operating speeds. *Soil & Tillage Research* 39: 61-73.

Siemens, J.C., J.A. Weber and T.H. Thornburn. 1965. Mechanics of soil as influenced by model tillage tools. *Transactions of the ASAE* 8(1): 1-7.

Soehne, W.H. 1956. Some principles of soil mechanics as applied to agricultural engineering. *Grundlagen der Landtechnik* 7: 11-27.

Stafford, J.V. 1979. The performance of rigid tine in relation to soil properties and speed. *Journal of Agricultural Engineering Research* 24(1): 41-56.

Stafford, J.V. 1984. Force prediction models for brittle and flow failure of soil by draught tillage tools. *Journal of Agricultural Engineering Research* 29 (1): 51-60.

Stafford, J.V. and D.W. Tanner. 1983a. Effect of rate on soil shear and soil-metal friction I. Shear strength. *Soil & Tillage Research* 3 (3): 245-260.

Stafford, J.V. and D.W. Tanner. 1983b. Effect of rate of soil shear strength and soil-metal friction. II. Soil-metal friction. *Soil & Tillage Research* 3(4): 321-330.

Vetrov, Y.A. and V.P. Stanevski. 1972. The investigation of the factors of the speed of cutting soils. *Mining, Construction and Highway Machines* 8, 21-26. Translated by W. R. Gill, National Tillage Machinery Laboratory, Auburn, AL.

Wismer, R.D. and H.J. Luth. 1972. Rate effects in soil cutting. *Journal of Terramechanics* 8 (3): 11-21.

Zeng, D. and Y. Yao. 1991. Investigation on the relationship between soil shear strength and shear rate. *Journal of Terramechanics* 28 (1): 1-10.

Zhang, Z.X. and R.L. Kushwaha. 1997. Theory and application of impact penetration. In *Proceedings of the Joint International Conference on Agricultural Engineering & Technology*, Vol. 1:251-260. December 15-18, 1997, Dhaka, Bangladesh.