土壤表殼阻力與關鍵穿透距離 (I)：量測方法

Soil Crust Impedance and Critical Penetration Distance (I)：Measurement Method

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摘　要

本文提出了關鍵穿透距離是除了土壤表殼阻力外，另一個影響種苗發芽出土的重要因素，並利用由下而上穿透的機械探針，建立了同時量測以上兩種因素的方法。實驗所觀察之表殼阻力機構包括圓錐剪斷與圓頂突出。隨著表殼之乾燥，表殼阻力機構亦由以圓錐剪斷爲主改變爲以圓頂突出爲主。表殼土壤潮濕時探針頭的增大會增加阻力，但是表殼乾燥時探針頭的大小不影響阻力。探針穿透速度由1至20cm/s範圍內的變化不影響表殼阻力。乾燥過程中表殼阻力隨時間及土壤的乾燥而增加。關鍵穿透距離亦隨著表殼之乾燥而增加。口袋型阻力計所量測之表殼阻力比用向上穿透的探針所量得者大，但兩者具良好的相關性。

關鍵詞：土壤表殼，阻力，穿透距離。

ABSTRACT

The cricital penetration distance has been suggested in this report as another important factor, besides the crust impedance, that influences seedling emergence through the soil crust. A laboratory method for measurement of these two factors was developed using a mechanical probe penetrating from below the crust. Observed crust braking mechanisms were primarily cone-shear when the crust was moist and shifted to dome-formation as the crust became dry. An increase in the probe size increased the measured impedance when the crust was moist, but the influence of probe size was insignificant when the crust dried. The effect of probe speed was not statistically significant for probe speeds from 1 to 20 cm/min. Crust impedance increased significantly with the drying of the crust. The critical penetration distance also increased as the crust dried. Crust impedance measured by a pocket type penetrometer correlated well with that measured by the upward penetrating probe. However, the pocket penetrometer tended to overestimate the impedance.

Keywords: soil crust, impedance, penetration distance

INTRODUCTION

A soil crust is a thin hard layer of small soil particles covering the soil surface. It is formed mainly from aggregate destruction by the impact of water drops during rainfall or sprinkler irrigation and from surface saturation by water application in excess of the infiltration capacity (Miller and Gifford, 1974). McIntyre (1958) described soil crusts as consisting of a 0.1 mm skin formed by rain drop impact containing no visible pores and a 1.5 to 3.0 mm thick region of reduced porosity created by plugging of larger pores by washed-in material. Formation of a soil crust gives rise to severe agronomic problems such as reduced water infiltration and permeability (McIntyre, 1958), increased run-off and soil erosion (Arndt, 1965a), and reduced diffusion of gas which may cause seedling respiration problems (Miller and Gifford, 1974). The most serious problem with crust formation is that the crust could, when dried, become a hard shell on top of planted seeds and prevent seedling emergence (Goyal, 1982; Awadhwal and Thierstein, 1985).

When a crust is formed above a seedling, the seedling has to rupture the crust to emerge. Arndt (1965a) described two types of rupture of the crust by emerging seedlings: cone-shear and dome-formation. Cone-shear is primarily observed when the soil crust is wet and acts like a homogeneous brittle medium. An inverted cone-shaped plug of soil is forced out of the crust by the elongation force of the seedling. Tensile failure of the soil surrounding the top of the seedling followed by extension of cracks to the surface at a slanted angle are likely responsible for formation of the cone (R. A. Schapery, 1988, personal communication). Dome-formation occurs primarily when the soil is dry. In this case, big pieces of the crust are cracked by the seedling, lifted simultaneously, and jammed into a dome-shaped structure. The mechanism of crust impedance in dome-formation is very complex. In order to emerge, the seedling has to overcome the gravitational force of the crust, cohesion between the crust and the soil below, compression resistance among adjacent crusts, and sliding friction between the crust and underlying soil.

Many methods have been developed to evaluate crust impedance. Modulus of rupture was proposed by Richards (1953) as an index of soil crust strength in relation to seedling emergence. The modulus of rupture was determined by the ultimate tensile strength of oven-dried soil briquettes. The fishing line method proposed by Bennett et al. (1964) employed a fishing line buried 2 cm deep in the soil. Crust impedance was the maximum force needed to pull the line up and break the crust. Another method was used by Bowen (1966) who applied hydraulic pressure to inflate a rubber balloon planted at seed depth. The pressure required to rupture the compressed soil cover was used as an indication of the mechanical impedance an emerging seedling might experience. Page and Hole (1977) compared crust impedance measured by three methods: the modulus of rupture, the fishing line, and a shear vane device. Results from all three methods correlated well with each other, but the shear vane was recommended because of its simplicity of use and small variability of the readings. The pocket type soil penetrometer has been widely employed for field and laboratory measurement of crust impedance in relation to seedling emergence (Gerard, 1980; Bilbro and Wanjura, 1982; Rathore et al., 1983; Joshi, 1987; Braunack and Dexter, 1988). The method basically involves pushing a probe downward into the soil surface to a certain depth while noting the maximum resistance force on the probe.

The above methods for measuring crust impedance share a common disadvantage of being indirect measurements for the impedance likely to be encountered by emerging seedlings. In light of the complexity of the crust breaking mechanisms discussed above, the direct evaluation of impedance on a mechanical probe penetrating the crust from below may be a more realistic method for measuring crust impedance. An underground apparatus was constructed by Arndt (1965b) in the field to determine the force required for a mechanical probe to emerge through the crust from below. Hadas and Stibbe (1977) used the same principle to measure crust impedance in the field by excavating a small cavity below the crust and pushing a pocket penetrometer up against the crust. Holder and Brown (1974) modified this method to measure crust impedance in the laboratory. In their work, crust was formed in soil boxes equipped with guide tubes on the bottom to allow a mechanical probe to penetrate the crust from below. The probe was supported by a balance which measured the impedance on the probe while being hand-raised by a scissors type jack. Many other researchers (Chaudhri et al., 1976; Hussain et al., 1985a, b; Painuli and Abrol, 1986) have adopted the upward moving probe for measuring crust impedance using methods similar to that of Holder and Brown.

One important aspect in the seedling-crust interaction is the penetration of the soil crust by the seedling. When the seedling penetrates the soil under a crust, impedance on the seedling escalates until a maximum value is reached. This maximum impedance normally is associated with the rupture of the crust by the seedling, either by cone-shear or dome-formation. The penetration distance of the seedling at this point is critical since it is the minimum elongation needed for the seedling to rupture the crust and emerge. After this point the impedance on the seedling drops, normally at a sharp rate, so that further elongation of the seedling faces a much less resistance. Therefore, a new term, critical penetration distance, is defined as the distance of penetration by the seedling when maximum crust impedance is encountered during its growth (Fig. 1).

The critical penetration distance is important since the ability of the seedling to emerge is determined by whether the seedling could elongate to the critical penetration distance, and whether it could exert sufficient force to overcome the crust impedance that climaxes at the critical penetration distance. Better seedling emergence can be expected if critical penetration distance of the crust is reduced. Considering the seedling as a column, the longer the critical penetration distance, the more likely the seedling would buckle thus reducing the maximum emergence force

(Chu, et al., 1992). Further, the longer the critical penetration distance, the more time the

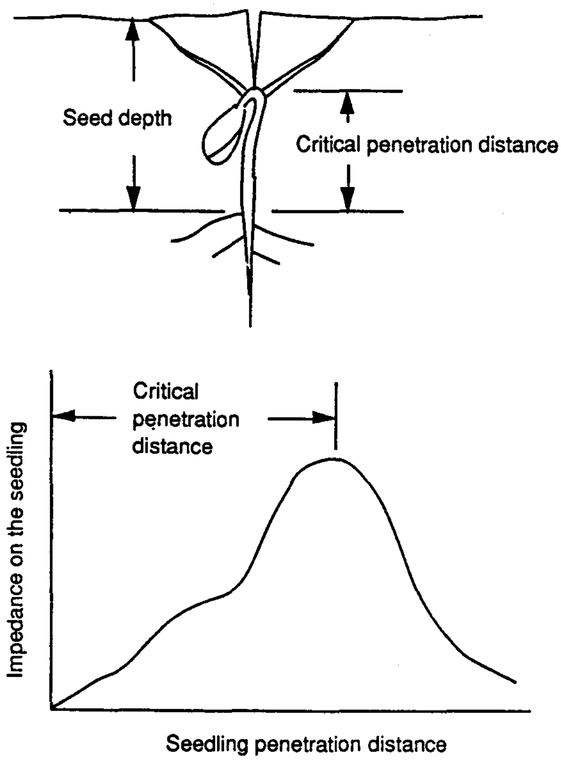

Fig. 1. Graphical representations of the critical penetration distance which is defined as the distance of penetration by the seedling when maximum crust impedance is encountered.

(Chu et al., 1992). Further, the longer the critical penetration distance, the more time the seedling has to stay under the crust. After a prolonged period under the crust, most seedling might not survive even though the crust is ruptured (Bowen, 1966).

The importance of the critical penetration distance has not been explicitly addressed in the literature possibly since there was not a proper method to measure it. Observational evidence suggests that critical penetration distance may increase with drying of the soil due to dome-formation. Holder and Brown (1974) reported that for a dry crust the impedance on an emerging probe increased until the crust was pushed above the original elevation of the surface. However, a lack of a continuous recording of crust impedance made it impossible to determine the critical penetration distance at which maximum impedance was encountered. Research is needed to develop a method to study the critical penetration distance and to quantify changes in critical penetration distance during formation and drying of the crust.

The method of Holder and Brown (1974) can be adopted for the simultaneous studies of crust impedance and critical penetration distance. A continuous recording of the impedance on the probe along with the distance of penetration by the probe while it penetrates the crust from below can provide information on both crust impedance and the critical penetration distance. Some factors related to this method have to be evaluated, e.g., probe size and speed. The lack of information on the effect of probe size has lead to disagreements over how the impedance should be interpreted: the crust impedance was reported by Holder and Brown (1974) in terms of force; but Hussain et al. (1985a, b) measure the crust impedance using a pressure unit.

The widely used pocket type penetrometer requires special attention. Basically, the method has been used without scrutiny since impedance is measured in a manner apparently different from real seedling emergence. However, the pocket penetrometer is perhaps the most convenient device available for field measurement of crust impedance. Hence it is valuable to evaluate this method in the laboratory and to establish quantitative information about the measurement as compared with the measurement by a probe penetrating from below.

The objectives of this research were (1) to establish the measurement method for the crust impedance and the critical penetration distance, (2) to study the critical penetration distance of the crust as affected by drying of the crust, and (3) to correlate measured impedance values by the probe with those measured by a pocket-type soil penetrometer.

MATERIALS AND METHODS

The method for measuring crust impedance was modified from that of Holder and Brown (1974). Crusts were formed in soil boxes, 43.2 cm long, 35.7 cm wide, and 11.5 cm high constructed with 1.6 cm thick plywood and painted. The upper edges of the boxes were beveled toward the outside to minimize water spalsh off the edges onto the soil surface. Twenty plastic tubes, 0.95 cm in inside diameter and 9 cm long, were mounted vertically in the bottom of the soil box in evenly spaced holes 7.5 cm apart. The tops of the tubes ended 2.5 cm below the top of the box. Six 1 cm diameter drainage holes were drilled in the bottom of the box and loosely covered. Fritted clay, commercially sold as a shop absorber, was used as a subgrade to facilitate drainage. The fritted clay was filled into the soil boxes to about 1.5 cm below the upper end of the tubes. The boxes were then hand-shaken and surface-compacted with a wood block to firmly settle the fritted clay.

A crust-forming soil, Lufkin loam (Verric Albaqualf, A1 Horizon), was used for this study. Characteristics of this soil are listed in Table 1. The soil was taken from the field at a moisture content of about 9 - 10% on the dry weight basis. After passing through a 47.5 mm sieve, the soil was either wetted by a water sprayer or air-dried to the desired moisture content. The soil was then stored in thick plastic bags for at least one day prior to each test. Before each test, the soil bag was shaken to ensure an even distribution of moisture within the soil. Prior to pouring the soil into the box, small wood rods as long as the rubes were inserted into each tube to prevent soil from entering the tubes. A 12 cm high collar was mounted around the top edge of the box to prevent soil from falling off the box during packing. Then the soil of desired moisture content was filled into the box to about 3 to 5 cm above the box. The soil boxes were then dropped twenty times from a height of about 2.5 cm to settle the soil and to achieve uniform packing. Finally, the collar was removed and excess soil above the box was scraped off to leave a flat surface. The wood rods were then removed from below and the soil boxes were sent for the simulated rainfall treatment.

Table 1. Soil characteristics* of the Lufkin loam soil used in this research.

Soil	Depth (mm)	pH	Organic matter	ESP[φ] (%)	Sand	Silt %	Clay
Lufkin loam	0-200	6.7	1.3	5	41	47	13

* From Soil Conservation Service, Official Soil Series Description.
φ Exchangeable sodium percentage.

The simulated rainfall was generated using a rotating-disk rainfall simulator constructed by Dr. K. Brown at Texas A&M University. The rainfall generated by this type of simulator approximated the characteristics of natural rainfall (Holder and Brown, 1974). Crusts were formed by exposing the filled soil boxes to the simulated rainfall with an intensity of 5.2 cm/hr for 12 minutes. By the end of the rain, the soil surface was smoothed and saturated with scattered small water ponds on the surface. Following the rainfall treatment, the soil boxes were placed in an air-conditioned laboratory and dried by banks of heat lamps. Nine 250 W infrared heat lamps were lined in a 3X3 matrix to apply a uniform radiation with a coefficient of variation of 6.3%. A double-dome net radiometer was used to measure the net radiation. A transformer adjusted the input voltage so that the net radiation averaged 250 kw/m^2 which approximates the amount of net radiation that is received on the ground on a clear day (Holder and Brown, 1974). Temperature and relative humidity in the laboratory were measured twice a day during the preparation and testing period. Average temperature was 22°C (cv=2.8%), and average relative humidity was 43% (cv=30%).

An Instron Universal Testing Machine was used to drive the mechanical probe through the crust (Fig. 2). The soil box was supported in front of the Instron Machine. A load cell platform was bolted to the crossbar of the Instron Machine extending to the front. A probe-bearing load cell was placed on the platform which was large enough to allow the probe to be positioned under any tubes of the soil box. The mechanical probe was made by soldering a ball bearing on a steel rod. Speed of the crossbar was selectable from 0.05 to 1000 mm/min. Crust impedance was measured by the load cell and continuously recorded by a chart recorder. The use of a chart recorder provided a complete trace of crust impedance during penetration of the probe. The working range of the load cell was selectable from 1 to 500 N. At the most sensitive setting the force signal can be accurately read to 0.01 N.

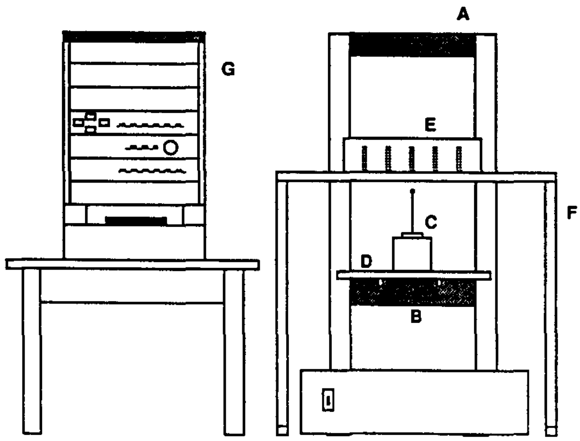

Fig. 2. Schematic diagram of equipment for the measurement of crust impedance. A: Instron machine, B: crossbar, C: load cell and the probe, D: load cell platform which is bolted on the crossbar, E: soil box, F: support for the soil box, and G: control panel.

Table 2. Experimental parameters of the experiments for effects of probe size and probe speed. The soil used had an initial moisture content of 10% (before rainfall) and no compaction.

Experiment	Time (hr) after rain for measurements	Probe diameter (mm)	Probe speed (cm/min)
I. Effect of probe size	6, 22, 65	3.18	5
	6, 22, 65	4.76	5
	6, 22, 65	6.35	5
II. Effect of probe speed	5, 19, 52	6.35	1
	5, 19, 52	6.35	5
	5, 19, 52	6.35	20

The effect of probe size was studied with probes of three diameters, 3.18, 4.76, and 6.35 mm. The 6.35 mm probe tip approximated the size of an emerging cotton hypocotyl. The purpose of this test was to determine the effect of probe size on the impedance measurement for soil crusts. The experiment was a randomized block design. Three soil boxes were prepared using soil at an initial moisture content of 10% and at no compaction. Crust impedance was measured at three different times (block) after rainfall representing wet, intermediate, and dry crust conditions (Table 2). At each time one soil box was used and crust impedance was measured by the three probes. Four to seven observations were made using each probe. Measurement of the impedance directly under a crack was avoided. A sample of the crust ruptured by the probe was taken to determine the moisture content of the crust. In addition, an extra soil box was prepared in the same manner but without the rainfall treatment. Penetration resistance was measured by the three probes to determine the impedance when crust was not formed.

The effect of probe speed was studied at three probe speeds, 1, 5, and 20 cm/min (Table 2) in a procedure similar to the above. It is noted that the actual growing speed of a cotton seedling is still much slower than the tested range. The elongation rate of a cotton seedling at the optimum condition is approximately 0.002 cm/-min (Arndt, 1945). Although the Instron machine had the capability to drive the probe at a slower rate, the prolonged penetration time with a slower probe might influence the moisture content of the crust and introduce errors into the measurement.

Penetrometer resistance of the crust was measured after each impedance measurement in the above. The penetrometer resistance was measured by pushing a 6.35 mm diameter blunt tip a distance of 2.5 cm into the soil at a speed of 1 cm/min. The first peak resistance was taken as the penetration resistance. Four to seven observations were made for each soil box. The penetrometer tip was mounted on either a cantilever-beam type force transducer or a load cell, depending on the level of force being measured. The penetration resistance was measured by keeping the force transducer or load cell stationary while moving the soil box up by the Instron crossbar. The force signal from the transducer was measured by a strain indicator and fed to a portable datalogger via a RS-232 interface. The force transducer had a maximum capacity of 30 N with an accuracy of 0.02 N. The load cell had a maximum capacity of 800 N with an accuracy of 0.5 N.

Table 3. Analysis of variance for the effect of probe size on measured crust impedance (N) for the soil without rain and for different measurement time after rainfall. Penetrometer resistance values are also listed for comparison.

Source	df	No rain	6 hrs after rain	22 hrs after rain	65 hrs after rain
		F values			
Probe size	2	10.89**	5.27*	0.75	0.08
		Means			
Probe size (mm)					
3.18		0.43b[φ]	2.57b	31.3	67.1
4.76		0.68a	3.32ab	38.5	62.6
6.35		0.60ab	4.25a	33.2	63.2
Penetrometer resistance		2.30	4.37	30.7	94.1

*,** Statistically significant at the 0.05 and 0.01 levels, respectively.
[φ] Means within a column followed by a common letter are not significantly different at the 5 percent level according to Duncan's Multiple Range Test.

RESULTS AND DISCUSSION

Both cone-shear and dome-formation types of crust rupture mechanisms were observed in this study. Cone-shear was primarily observed on moist soil, while dome-formation was dominant when the crust had dried. In a dome-formation type of probe emergence, large pieces of crust were lifted and jamming among adjacent crusts was observed. As the jamming happened, the maximum impedance values tended to occur in the form of double peaks. The first peak was likely responsible for the breaking of the crust and its separation from the surrounding soil, but the second and sometimes higher peak would be the result of jamming of the crust when friction and compression between neighboring crusts added to the resistance on the probe.

The effect of probe size on the measured impedance was first analyzed for each measurement time. The measured crust impedance was significantly affected by probe size when crust was not formed and when the crust was still relatively moist at 6 hours after rainfall (Table 3). Effects of probe size were not significant in the two later measurements when the crust was relatively dry. Morton and Buchele (1960) measured the emergence energy of a mechanical probe penetrating from beneath a block of compacted soil. The emergence energy increased as the probe size increased. This can be explained since a larger probe has to displace more soil as it penetrates. However, when a soil crust is formed, the emergence mechanisms became so complex that the effect of size of the probe appeared to be masked. Arndt (1965b) used different probes to study the crust impedance in the field. In his report, probe sizes increased by nine-fold did not significantly increased the measured impedance. Results of this research present a bridge to the two studies by showing the change in significance of the effect of probe size during drying of the soil crust. This shift of significance should be taken into account when measuring and reporting crust impedance values. When probe size is not significant, crust impedance should be measured and reported in terms of force instead of pressure.

Crust impedance measurements using probes of three sizes are analyzed in Table 4. The measurement for soil without rainfall treatment and for crusts at three different times after rainfall are grouped into one simplified variable "time (T)". The analysis in Table 4 combines effects of probe size and time in one model with an R^2 value of 0.92. The effect of probe size is not significant in this overall model. The variation of crust impedance due to the variation of probe size appeared to be overpowered by the effect of time. Time of measurement significantly influenced crust impedance. The measured resistance on the probe was least when the soil was not subjected to rain. After rainfall, the impedance increased rapidly with time. Crust impedance measured by the 6.35 mm probe rose to 4.24 N after only 6 hours of drying. After 22 hours, the impedance was 33.2 N, already three times as high as the maximum emergence force the cotton seedling could possibly generate (Chu et al. 1991). It is noted that the impedance observed may be higher than that in the field. Hadas and Stibbe (1977) found that the field impedance was much smaller than the laboratory result. The soil used in the laboratory was crushed and sieved, had fewer macropores and became uniformly compacted after rainfall and, therefore, may produce a harder crust.

It appears that an exponential relationship exists between crust impedance and the moisture content of the crust. For instance, the crust impedance measured by the 6.35 mm probe increased from 4.25 N to 33.2 N when the soil moisture content dropped from 7.5% to 1.4%. But another 30 N increase in the impedance came with a further decrease of the soil moisture content of only 0.4%. This is important since a small change in the soil moisture content when the soil is dry would greatly change the impedance. This observation agrees with that of Hadas and Stibbe (1977). The results indicates that field measurement of the crust impedance should be made around the same time in the day since the soil moisture content changes diurnally.

Results of the effect of probe speed are analyzed in Table 5. The speed of the probe in the range between 1 and 20 cm/min did not affect the measured crust impedance regardless of the time of measurement and moisture content of the crust.

The data from probe size and probe speed tests were used to determine how critical penetration distance changed as the crust dried (Table 6). In the probe size test, critical penetration distance increased from 11.4 mm at 6 hr after rain to 15.7 mm at 65 hr after rain. In the probe speed test, critical penetration distance increased from 9.1 mm at 5 hr to 15.8 mm at 52 hr. The effect of time on critical penetration distance was significant in both cases. Critical penetration distance increased as the crust breaking mechannism shifted from primarily cone-shear to primarily dome-formation during drying of the crust. An increase in critical penetration distance means that the hypocotyl must elongate more before the crust is ruptured. This may delay or even inhibit seedling emergence, depending on the seed reserve energy and the ultimate impedance of the crust.

Compared with crusted soil, the critical penetration distance of uncrusted soil was much smaller (Table 6). For a larger critical penetration distance, the seedling has to elongate more before rupturing the crust. This greater requirement for hypocotyl elongation is deleterious to seedling emergence since the seedling has to ex pend more energy before emergence and the possibility of buckling is increased for a longer hypocotyl. Therefore, the crusting problem results from not only increased physical impedance but also greater critical penetration distance.

Table 4. Analysis of variance for effects of time of measurement and probe size on measured crust impedance. $R^2 = 0.92$.

Source	df	F value	Pr > F
Time (T)	3	182.39	0.0001
Probe size (P)	2	0.11	0.8950
T * P	6	0.42	0.8619

Time	Mean impedance (N)
No rain	0.57c*
6 hrs after rain	3.38c
22 hrs after rain	34.3b
65 hrs after rain	64.3a

* Means within a column followed by a common letter are not significantly different at the 5 percent level according to Duncan's Multiple Range Test.

Table 5. Analysis of variance for effects of time of measurement and probe speed on measured crust impedance. Penetrometer resistance values are also listed for comparison.

Source	df	F value	Pr > F
Time (T)	2	279.72	0.0001
Probe speed (S)	2	0.43	0.6521
T * S	4	0.47	0.7550

Time	Mean impedance (N)	Penetrometer resistance (N)
5 hrs after rain	2.10c*	2.53
19 hrs after rain	23.7b	30.0
52 hrs after rain	69.3a	68.1

* Means within a column followed by a common letter are not significantly different at the 5 percent level according to Duncan's Multiple Range Test.

Table 6. Mean values of critical penetration distance as affected by time of measuerement after rainfall or without rainfall treatment. Data were taken from the probe size and probe speed tests.

Experiment	Time after rainfall (hr)	Crust moisture (%)	Critical penetration distance (mm)
I. Probe	No rain	9.6	4.3*c
size test	6	7.5	11.4b
	22	1.4	11.9b
	65	1.0	15.7a
II. Probe	5	12.0	9.1b
speed test	19	1.6	14.5a
	52	1.0	15.8a

* Means within a column followed by a common letter are not significantly different at the 5 percent level according to Duncan's Multiple Range Test.

It is further noted that the critical penetration distances obtained in this experiment were only a fraction of the depth of the top soil (2.5 cm). The depth of the top soil has been traditionally used as a criterion for the minimum elongation needed by the seedling to emerge. Under crusted conditions, however, the critical penetration distance may serve as a more appropriate counterpart to the seedling elongation since crust impedance plays a determinant role for seedling emergence.

Because no significant differences were detected for the three probe speeds using the 6.35 mm probe, the impedance values were averaged. The average impedance values and the measurements made by the 6.35 mm probe in the probe size experiment were used to correlate with the measurements made by the pocket-type penetrometer (Fig. 3). It was found that the two measurements correlated very well with an R-square value of 0.92. However, the pocket-type penetrometer overestimated the crust impedance by about 19 percent. The difference between the two methods increased as the crust impedance increased. Furthermore, it has been shown that

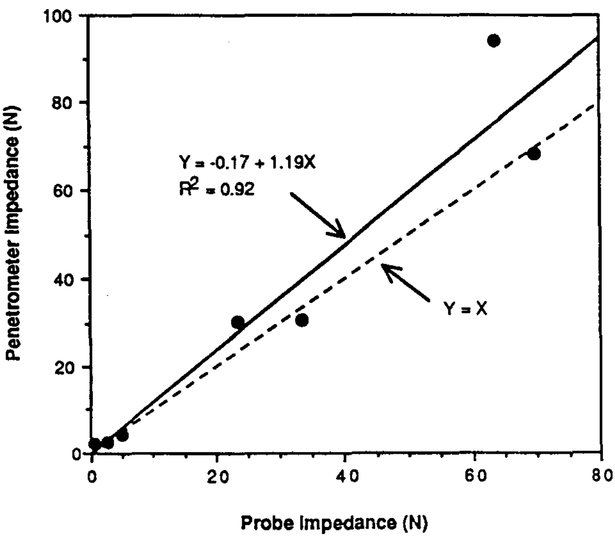

Fig. 3. Correlation between the crust impedance values measured by the pocket-type penetrometer and the mechanical probe penetrating from below the crust.

the size of the probe does not affect the impedance measurement. This might not be true for measurements made with the pocket-type pene-

Fig. 4. Penetration resistance vs. penetration

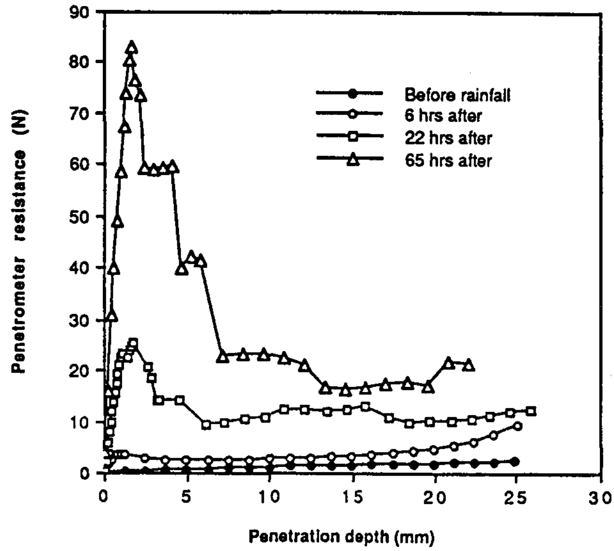

Fig. 4. Penetration resistance vs. penetration depth at different times before or after rainfall. Penetration resistance was measured by a pocket-type penetrometer.

trometer as they are normally expressed in terms of pressure units. Therefore the laboratory result holds true only for this particular penetrometer tip and experimental conditions, and field testing is needed to verify the laboratory result.

The mechanism of crust-breaking was very different for the two methods. Crust-breaking by the upward-moving probe was described as either a dome-formation or an inverted-cone breaking. On the other hand, the penetrometer broke the crust by creating an upright cone-shaped cavity under the crust. Figure 4 shows the penetration resistance versus depth of penetration of the pocket-type penetrometer. Each curve is the average of four to seven observations. On the soil not subjected to rainfall, the penetration resistance increased steadily as the tip was pushed into the soil surface. After rainfall, however, a local maximum resistance occurred near the soil surface. When the crust dried, the local maximum resistance rose sharply. The penetration resistance was influenced by two factors. One is the resistance resulting from compaction of soil underneath the penetrometer tip. This accounted for the steady increase in the penetration resistance. The other is the resistance caused by failing of the thin surface layer of crust which resulted in the peak resistances. The peak resistance occurred only in the first few millimeters of penetration.

CONCLUSIONS

Measurement of crust impedance using a mechanical probe penetrating from below the crust showed that an increase in the probe size increased the measured impedance when the crust was moist. This difference disappeared as the crust dried. The effect of probe speed was not statistically significant for the range studied. Crust impedance increased significantly with time of measurement as the crust became dried.

The critical penetration distance was defined in this research as the distance of penetration by the seedling when maximum crust impedance is encountered. Critical penetration distance increased as the crust breaking mechanism shifted from primarily cone-shear to dome-formation.

The crust impedance measured by a pocket-type penetrometer correlated well with that measured by the probe. However, the pocket penetrometer overestimated the crust impedance.

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