# 土壤表殼阻力與關鍵穿透距離 (II)：初始土壤含水率、壓力與乾燥速率之影響

## Soil Crust Impedance and Critical Penetration Distance (II): Effects of initial Soil Moisture Content, Compaction and Drying Rate


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### 摘 要

本研究探討初始土壤含水率、土壤表面所施之壓力、以及乾燥速率對土壤表殼阻力及關鍵穿透距離之影響。初始土壤含水率及壓力之增加使土壤表殼阻力以線性增加。土壤受雨後5，18，及54小時所量測之表殼阻力，在初始土壤含水率由5%提高爲15%時，分別增加了43，174，及233%。表面所施壓力由0增加至20kPa時，表殼阻力在三個量測時間所增加的量分別爲34，30，及48%。關鍵穿透距離隨著初始土壤含水率之增加而線性地增加。量測時間增加時，關鍵穿透距離由5小時的6.9mm增加爲54小時的10.0mm。壓力對關鍵穿透距離的影響及乾燥速率對表殼阻力的影響皆不顯著。



關鍵詞：表殼阻力，關鍵穿透距離，含水率，壓力，乾燥。



### ABSTRACT

Effects of initial soil moisture content, surface compaction, and drying rate on crust impedance and the critical penetration distance were studied. Crust impedance increased linearly with an increase in initial soil moisture content and surface compaction. At three measurement times, 5, 18, and 54 hr after rainfall, crust impedance increased 43, 174, and 233%, respectively, eith the increase in initial soil moisture content from 5 to 15 percent. An increase in surface compaction from 0 to 20kPa increased crust impedance by 34, 30 and 48% at 5, 18, and 54 hours after rainfall, respectively. The critical penetration distance increased linearly as the initial soil moisture content increased. The critical penetration distance increased with time of measurement from 6.9 mm at 5 hr to 10.0 mm ar 54 hr after rainfall. The effect of compaction on the critical penetration distance and the effect of drying rate on crust impedance were not significant.



Keywords: crust impedance, critical penetration distance, moisture, compaction dring


## INTRODUCTION

Crust impedance is the result of complex mechanisms involved in crust breaking during seedling emergence. The influencing factors are the mechanical strength of the crust both in tension and compression, gravitational forces of the crust, and cohesion and sliding friction between the crust and underlying soil. The last two factors are influenced by the geometry of adjacent crusts over the seedling, hence are affected by the pattern of cracking of the crust and location of the seedling in relation to the cracks (Arndt, 1965a; Miller and Gifford, 1974). Characteristics of soil that usually create crusts of high mechanical strength include high silt content, high exchangeable sodium (ESP), and low organic matter (Miller and Gifford, 1974). These are all related to low aggregate stability to resist structural destruction and slaking of aggregates under impact of water. The result is a dense, massive structure which becomes a hard crust upon drying.

The strength of soil crusts depends upon the strength of particle-to particle bonds which may be determined by bond strength and number of contacts (Kemper et al., 1974; Uehara and Jones, 1974). In crusting soils of the arid and semi-arid regions, the most likely cementing agent is silica ($SiO_2$), which exists in gel-like surface coatings of soil particles and transforms from a viscous liquid to an elastic solid upon drying (Uehara and Jones, 1974). The number of contact points among soil particles is related to the size of the particle. A 10-fold decrease in diameter of spherical particles increases the number of particles contained in a unit soil volume by 1000-fold and may result in a proportionate increase in potential contact areas (Uehara and Jones, 1974). Accordingly, soils high in silt have sufficient particle-to-particle contacts to form strong bonds as the soil dries, therefore causing a hard crust (Miller and Gifford, 1974).

Field observations show that frequency of crusting is much reduced when particles exceed silt size. Because of the higher swelling and shrinking properties of clay, soil crusts high in clay tend to crack upon drying, thus reducing impedance to emerging seedlings (J. E. Morrison, Jr., 1989, personal communication). Clay also plays a positive role in stabilizing natural soil aggregates against disintegration during wetting (Kemper and Koch, 1966). However, the stabilizing effect of clay can be altered by the exchangeable sodium (ESP) in the clay. High sodium content in the exchange complex of clay makes particles disperse readily and become compacted soon after wetting. Soils are more susceptible to crusting with an ESP of about 6 and higher (Loveday, 1976).

Soils with higher organic matter contents, i.e., 2 or 3% or more, are less susceptible to crusting (Kemper and Miller, 1974). Organic matter acts in two ways to hold the particles together in fairly stable aggregates so that they resist slaking in water. Organic substances can reduce interaction of water with the clay surface thus reducing the damaging effect of water resorption. Also, long organic molecules act as glues to physically or chemically bind soil particles together (Uehara and Jones, 1974).

Many factors that may affect the mechanical strength of the crust have been studied using modulus of rupture as an index for crust strength. Modulus of rupture increased with puddling and decreased with increasing soil moisture content, temperature of drying, and number of wetting and drying cycles. It is also affected by rainfall, soil texture, type of clay, and bulk density (Lemos and Lutz, 1957). The crust is less penetrable and harder (higher modulus of rupture) with higher initial bulk density and water content of the top soil, slower drying, and smaller aggregates on the surface (Hillel, 1960). Amount of clay, method and rate of wetting, as well as the degree of saturation may influence the modulus of rupture (Kemper et al., 1974). More recently, Braunack and Dexter (1988) studied crust strength using a modified modulus of rupture test on naturally formed crusts. They concluded that average crust strength decreased as aggregate sizes increased from 0.4 to 3 mm, then changed very little for further increases in aggregate size up to 7.5mm.

Despite much research results, however, the applicability of modulus of rupture has been questioned by many researchers as to whether it could represent crust impedance on the seedling in field situations (Lemos and Lutz, 1957; Arndt, 1965a; Uehara and Jones, 1974; Page and Hole, 1977). A probe penetrating from below the crust was proposed by Arndt (1965b) as a more realistic method for measuring crust impedance.

Using this method, he reported that crust impedance increased with decreasing soil water content and increasing depth of soil on the probe. Soil moisture is the prime factor influencing crust impedance (Hussain et al., 1985a). Drying of the crust increases its mechanical strength and makes it hard. Hadas and Stibbe (1977) fround an exponential relationship between crust impedance and moisture content of the crust. When the soil became dry, relatively smaller decreases in soil moisture cause larger increases in crust impedance. The result by Holder and Brown (1974) showed that crust impedance increased until soil moisture content was reduced to about 2% at which a sharp drop in impedance occurred, possibly because of cracking of the crust. Painuli and Abrol (1986) reported that crust impedance increased with ESP, amount of water applied, and temperature, but decreased with increasing evaporative demand. Other factors influencing crust impedance are rainfall intensity and duration, aggregate size, soil texture, and organic matter content (Holder and Brown, 1974; Hussain et al., 1985a, b).

Surface compaction of seed-covering soil could improve emergence, depending on the type of soil. The emergence percentage of cotton increased when surface compaction was applied on two types of clay soils (Holekamp et al., 1962; Morrison, 1989). Slight compaction increases the seed-soil area of contact, thereby increasing the rate of water flow to the seed and improving germination and emergence. Prasad (1988) observed that germination time was reduced by compaction of the seed growing media until a critical value was reached. Compaction of the surface soil also could better seal off the soil surface and reduce water loss. Bowen (1966) reported that the time required for the drying front to reach a seed depth of 2.5 cm was increased by a surface compaction of 7 kPa on soil at intermediate levels of moisture content. Compaction also could improve lateral support to the seedling and increase the emergence force as observed by Chu et al (1991).

Excessive compaction of the surface soil certainly could create a crust strong enough to inhibit emergence. Surface compaction has little effect on impedance when the soil at planting is air-dry, but surface compaction could greatly increase mechanical impedance of the crust when the initial soil moisture content is increased (Bowen, 1966). Since compaction and initial soil content are readily controllable by tillage and planting operations, information about effects of compaction and initial soil moisture and their interactions on crust impedance would be of value for management of the crusting problem.

The purpose of this study was to evaluate effects of initial soil moisture content and compaction on crust impedance and critical penetration distance. Experiments were carried out using the laboratory method reported in the first part of this report. In addition, the effect of drying rate of the crust on crust impedance was investigated.

## MATERIALS AND METHODS

The soil and the method for preparing the soil boxes and measuring crust impedance followed that in the first part of this study. Effects of initial soil moisture content and compaction were studied with a split plot of a two factor factorial in a randomized block design. The factorial treatments included three initial soil moisture contents (5, 10, and 15% on a dry weight basis) and three compaction levels (0, 10, and 20 kPa). The initial soil moisture content was the moisture content of the soil in the prepared soil boxes before applying rainfall. For the compaction effects, soil in the boxes was compacted at either 10 kPa or 20 kPa using a manually operated hydraulic soil compactor which applied a predetermined pressure on the soil surface. This range of surface compaction approximates those created by common surface-compaction wheels. The experiment schedule for the nine combination treatments are shown in Table 1. The crust impedance was measured for each soil box at three times (subplots) after rainfall, 5, 18, and 54 hr, by a 6.35 mm diameter probe penetrating from beneath at 5cm/min. The timing was selected in order to represent crust moisture conditions as wet, intermediate, and dry. At each time after rainfall 3 to 4 measurements of crust impedance were made. Because the soil drying rates might be different among different treatments, the cur-

Table 1. The experiment schedule to start the nine combination treatments of three initial soil moisture contents (5, 10, and 15%) and three compactions (0, 10, and 20 kPa) on three consecutive days.

| Day 1 | Day 2 | Day 3 |
|---|---|---|
| 5%-0 kPa | 5%-10 kPa | 5%-20 kPa |
| 10%-10 kPa | 10%-20 kPa | 10%-0 kPa |
| 15%-20 kPa | 15%-0 kPa | 15%-10 kPa |

Table 2. Experimental parameters of the experiments for effects of initial soil moisture content, compaction, and drying rate on crust impedance. The mechanical probe had an diameter of 6.35 mm and penetrated the crust from below at 5 cm/min.

| Experiment | Time (hr) after rainfall for each measurement | Initial moisture (%) | Compaction (kPa) | Net Radiation ($W/m^2$) |
|---|---|---|---|---|
| I. Effects of | 5, 18, 54 | 5 | 0 | 250 |
| initial soil | 5, 18, 54 | 5 | 10 | 250 |
| moisture content | 5, 18, 54 | 5 | 20 | 250 |
| and compaction | 5, 18, 54 | 10 | 0 | 250 |
| | 5, 18, 54 | 10 | 10 | 250 |
| | 5, 18, 54 | 10 | 20 | 250 |
| | 5, 18, 54 | 15 | 0 | 250 |
| | 5, 18, 54 | 15 | 10 | 250 |
| | 5, 18, 54 | 15 | 20 | 250 |
| II. Effect of | 20, 70, 191 | 10 | 0 | 0 |
| drying rate | 8, 24, 165 | 10 | 0 | 125 |
| | 5, 18, 54 | 10 | 0 | 250 |

Table 3. F values for the analysis of variance for effects of initial soil moisture content and compaction on crust impedance at three times after rainfall.

| Source of variation | df | Time (hr) after rainfall 5 | 18 | 54 |
|---|---|---|---|---|
| Replication (R) | 1 | 0.00 | 0.22 | 0.04 |
| Compaction (C) | 2 | 9.17* | 1.81 | 5.07* |
| Initial moisture (M) | 2 | $3.99^{\varphi}$ | 9.18* | 22.17* |
| C * M | 4 | 1.02 | 1.36 | 2.40 |
| Crust moisture (CM) | 1 | 2.45 | $5.51^{\varphi}$ | 1.70 |
| Error | 7 | | | |
| Contrast | | | | |
| Linear C | 1 | 16.02* | ---- | 10.02* |
| Quadratic C | 1 | 2.40 | ---- | 0.20 |
| Linear M | 1 | 7.02* | 15.69* | 44.34* |
| Quadratic M | 1 | 0.17 | 6.73* | 0.14 |
| Average crust moisture content (%) | | 10.60 | 2.64 | 1.42 |
| $R^2$ | | 0.88 | 0.87 | 0.92 |

$\varphi$, * Statistically significant at the 0.10 and 0.05 levels, respectively.

rent moisture content of the crust at the time of the impedance measurement was used as a covariate in the model. The effect of the crust moisture content, therefore can be calculated and excluded from the analysis. Entire treatments were replicated once. Experimental parameters are listed in Table 2.

The effect of drying rate on crust impedance was studied with three drying rates that were controlled by varying the net radiation applied by the heat lamps. The net radiations were 250 $W/m^2$, 125 $W/m^2$, and zero (air-dry). The experiment was carried out and analyzed using the same method in the above in a one-way split plot design. Because the soil dried at different rates, the crust impedance measurements were made at different times after rainfall so that the crust moisture content would be close among boxes (Table 2). Crust moisture content was taken as a covariate in the statistical model.

## RESULTS AND DISCUSSION

Effects of initial soil moisture content and compaction on crust impedance were first analyzed for each time after rainfall using the crust moisture content as a covariate. The analysis of variance showed that effects of the covariate were not significant at the 5 percent level for all the three times after rainfall (Table 3). Although moisture content of the crust was a determining factor in crust impedance, the variation of the crust moisture content among the soil boxes at each stage was very small, making the covariate non-significant. Therefore, the covariate was excluded, and an analysis of variance for the over-

Table 4. F values for the analysis of variance for effects of initial soil moisture content, compaction, and time after rainfall on crust impedance and the critical penetration distance.

| Source of variation | df | Crust impedance | Critical penetration distance |
|---|---|---|---|
| Replication (R) | 1 | 2.91 | 1.15 |
| Compaction (C) | 2 | $3.34^{\varphi}$ | 0.89 |
| Initial moisture (M) | 2 | 24.89** | $4.10^{\varphi}$ |
| C * M | 4 | 2.08 | 1.54 |
| C * M * R (Error a) | 8 | 1.35 | 0.93 |
| Time (T) | 2 | 183.63** | 14.90** |
| C * T | 4 | $2.30^{\varphi}$ | 0.28 |
| M * T | 4 | 16.93** | 1.67 |
| C * M * T | 8 | 1.84 | 0.46 |
| Error (b) | 18 | | |
| Contrast | | | |
| Linear M | 1 | --- | 4.53* |
| Quadratic M | 1 | --- | $3.14^{\varphi}$ |
| $R^2$ | | 0.97 | 0.78 |

$^{\varphi}$, *, ** Statistically significant at the 0.10, 0.05, and 0.01 levels, respectively.

all model was performed, which included initial soil moisture content, compaction, time after rainfall, and interactions among the above three factors (Table 4). Crust impedance was signifiicantly affected by initial soil moisture content, time after rainfall, and the interaction between initial moisture content and time after rainfall at the 1 percent level and by compaction and its interaction with time after rainfall at the 10 percent level. The model accounted for 97% of the variation in crust impedance.

Because of the interaction between effects of time after rainfall and those of the other two factors, initial soil moisture content and compaction, further analysis was carried out for each time after rainfall using Table 3. At 5 hours after rainfall, when the average crust moisture content was 10.60%, crust impedance was linearly increased with an increase in either compaction or initial soil moisture content (Table 3). The effect of compaction was significant at the 5 percent level, while the effect of initial soil moisture content was significant at the 10 percent level. At 18 hours after rainfall, the average crast moisture content dropped to 2.64%. The effect of initial moisture content was significant at the 5 percent level. The contrasts for both linear initial moisture content and quadratic initial moisture content were significant indicating that crust impedance increased with an initial moisture content but leveled off at higher moisture values. The effect of compaction was not significant, although the mean impedance values increased with an increase in compaction (Table 5). At 54 hours after rainfall, the crust further dried to a moisture content of 1.42%. The effects of both initial soil moisture content and compaction were significant at the 5 percent level. Crust impedance was linearly related to both factors. In conclusion, an increase in initial soil moisture con-

Table 5. Least square means of crust impedance (N) at three compactions, three initial soil moisture contents, and three times after rainfall. Soil is a Lufkin loam.

| Time (hr) | Compaction (kPa) | Initial moisture content (%) 5 | 10 | 15 | Mean |
|---|---|---|---|---|---|
| 5 | 0 | 2.15 | 3.80 | 3.70 | 3.22 |
| | 10 | 3.33 | 3.84 | 5.13 | 4.10 |
| | 20 | 3.99 | 4.20 | 4.74 | 4.31 |
| | Mean | 3.16 | 3.95 | 4.52 | 3.88 |
| 18 | 0 | 11.6 | 31.7 | 42.2 | 28.5 |
| | 10 | 21.1 | 37.0 | 47.6 | 35.2 |
| | 20 | 15.8 | 51.6 | 43.4 | 36.9 |
| | Mean | 16.2 | 40.0 | 44.4 | 33.5 |
| 54 | 0 | 27.6 | 29.8 | 84.6 | 47.3 |
| | 10 | 30.2 | 64.0 | 90.1 | 61.4 |
| | 20 | 26.0 | 80.3 | 103.7 | 70.0 |
| | Mean | 27.9 | 58.0 | 92.8 | 59.6 |

tent significantly increased crust impedance in a linear manner. An increase in surface compaction produced a similar result but was not as consistent as the effect of initial moisture content.

While the moisture content of the crust is a major factor influencing crust impedance, the initial moisture level of soil also has been shown to be an effective factor in determining impedance of the crust. An increase in initial soil moisture content from 5 to 15% increased mean crust impedance by 43, 174, and 233% at 5, 18, and 54 hours after rainfall, respectively (Table 5). The fact that percentage increase in crust impedance becomes greater as the time after rainfall increases indicates the close interaction between the effect of initial soil moisture content and that of time after rainfall, hence that of the dryness of the crust.

The magnitude of the effect of compaction was not as large as that of initial soil moisture content. An increase in surface compaction from 0 to 20 kPa increased average crust impedance by 34, 30, and 48% at 5, 18, and 54 hours after rainfall, respectively (Table 5). The interaction between the initial soil moisture content and surface compaction deserves noting. The average crust impedance increased only 11% when the initial soil moisture content was 5%. At 54 hours after rainfall, surface compaction did not increase crust impedance when the initial soil moisture content was 5%. Bowen (1966) reported that surface compaction had little effect on impedance when the soil at planting was air-dry, but surface compaction seriously increased the mechanical impedance when the initial soil moisture content was increased.

The emergence force data of some common dicotyledon seedlings are shown in Table 6. Based on a comparison between the emergence force and the crust impedance, all but the soybean

Table 6. Emergence force of some common dicotyledon seedlings.

| Crop | Force (N) | Source of data | Remarks |
|---|---|---|---|
| Cotton | 11.4 | Chu et al. (1991) | 27°C, -0.1 bar |
| Peanut | 8.2 | Inouye et al. (1979) | Mean of three species |
| Soybean | 1.2 | Inouye et al. (1979) | Mean of three species |
| Sword bean | 12.5 | Inouye et al. (1979) | Var. Natamame |

seedlings could emerge from the Lufkin loam soil in this research at 5 hours after rainfall. At 18 hours after rainfall, only the sword bean seedling could overcome the crust impedance of the soil with an initial moisture content of 5% and zero compaction. At 54 hours after rainfall, the least crust impedance from the nine treatments was more than twice as much as the emergence force of any of the species in Table 6. This example demonstrates the severity of the crusting problem with this soil.

The above discussion indicates the importance of timing of planting in relation to a crust-forming rainfall. Rathore et al. (1983) reported that the seedling has a much better chance of emerging if the crust is formed a few days after sowing. Since the crust impedance increases with the length of time after rainfall, the elongation of the seedling has to be such that the seedling could break the crust before crust impedance increases beyond the emergence force of the seedling. Planting the seeds when the weather forecast predicts a lower probability of rainfall in the next few days will then help reduce the risk of crusting.

The analysis of variance for the effect of initial soil moisture content, compaction, and time after rainfall on the critical penetration distance is shown in Table 4. The effect of the crust moisture content was not significant at the 10% level and was not included in the model. The effect of time after rainfall on the critical penetration distance was significant at the 1 percent level, while the effect of initial moisture content was significant at the 10 percent level. The effect of compaction was not significant. The mean values of the critical penetration distance increased about 45% from 6.9 mm at 5 hours after rainfall to 10.0 mm at 54 hours after rainfall (Table 7). The correlation coefficient between critical penetration distance and the crust impedance was only 0.35. Since the crust impedance also increases with the length of time after rainfall, seedlings emerging at a slower rate will likely confront a higher impedance as well as a longer penetration distance necessary to rupture the crust. If the seedling can be simulated by a column, the ability of the seedling to resist buckling is negatively proportional to the length-square of the seedling according to the Euler column formula (Shigley, 1989). Therefore, this increased penetration distance will reduce the critical load that could be supported by the seedling.

The effect of drying rate of the soil on crust impedance is presented in Table 8. The result shows that the effect of drying rate was not statistically significant, but the mean values of the crust impedance had a tendency to increase with slower drying. Hillel (1960) reported that slow drying at a higher soil moisture content increased the crust strength as measured by the modulus of rupture.

Based on experimental results from this research, a speculation of a planting method for reducing crust impedance is presented in the following. Because crust impedance increases with

Table 7. Least square means of the critical penetration distance (mm) at three compactions, three initial soil moisture contents and three times after rainfall.

| Time (hr) | Compaction (kPa) | Initial moisture content (%) 5 | 10 | 15 | Mean |
|---|---|---|---|---|---|
| 5 | 0 | 6.2 | 7.7 | 6.2 | 6.7 |
| | 10 | 7.7 | 8.5 | 5.4 | 7.2 |
| | 20 | 7.8 | 7.1 | 5.3 | 6.7 |
| | Mean | 7.2 | 7.8 | 5.6 | 6.9 |
| 18 | 0 | 11.2 | 9.0 | 10.5 | 10.2 |
| | 10 | 10.8 | 10.0 | 6.9 | 9.2 |
| | 20 | 12.1 | 10.0 | 5.6 | 9.2 |
| | Mean | 11.3 | 9.7 | 7.7 | 9.6 |
| 54 | 0 | 9.8 | 12.2 | 10.8 | 10.9 |
| | 10 | 9.6 | 11.8 | 8.2 | 9.9 |
| | 20 | 10.1 | 8.7 | 8.5 | 9.1 |
| | Mean | 9.8 | 10.9 | 9.2 | 10.0 |

an increase in the initial soil moisture content, a dry layer of soil covering the seedbed at planting may reduce crust impedance. Since it is initially dry it poses minimum danger to increasing the impedance. The dry surface layer also could reduce evaporation and reserve moisture in the underlying soil. Since the thickness of the crust normally is less than 5 mm and since moist soil is needed around the seed, this dry surface layer should be made to be less than 1 cm deep so that the seed could be covered by a layer of moist soil first. The dry surface layer should be composed of aggregates in a proper size range to further reduce the risk of crusting. Braunack and Dexter (1988) reported that an aggregate size between 2 to 4 mm generated the least crust impedance. Therefore, the planter should be designed to cover the seed with a layer of moist soil then another 1 cm layer of dry soil with medium aggregate size (2-4 mm). Where compaction is needed as in some regions, the surface layer of dry soil should be applied after compaction. This suggestion is based on the present results obtained in a laboratory environment and needs to be tested under field conditions.

## CONCLUSIONS

Crust impedance was significantly affected by initial soil moisture content, compaction, time after rainfall, and the interaction among these factors. Crust impedance increased linearly with an increase in initial soil moisture content and surface compaction. An increase in initial soil moisture content from 5 to 15 percent increased the impedance of dry crusts by 233%. The increase in surface compaction from 0 to 20 kPa increased crust impedance by 34, 30, and 48% at 5, 18, 54 hours after rainfall, respectively. Critical penetration distance increased with the

Table 8. Analysis of variance for the effect of drying rate and time after rainfall on crust impedance. $R^2 = 0.98$. The crust moisture content was excluded from the model for being non-significant.

| Source | df | F value | PR > F |
|---|---|---|---|
| Replication (R) | 1 | 2.26 | 0.2713 |
| Drying rate (D) | 1 | 4.39 | 0.1854 |
| R * D (Error a) | 2 | 0.55 | 0.6050 |
| Time (T) | 2 | 133.81 | 0.0001 |
| D * T | 4 | 1.82 | 0.2442 |
| Error (b) | 6 | | |

| Net radiation ($W/m^2$) | Mean crust impedance (N) |
|---|---|
| 0 | 27.7 |
| 125 | 25.5 |
| 250 | 22.6 |

length of time after rainfall and initial moisture content of the soil. The effect of compaction on the critical penetration distance and the effect of drying rate on crust impedance were not significant.

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