SENSING HARD PAN DEPTH WITH GROUND-PENETRATING RADAR

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ABSTRACT

An experiment was performed in soil bins to determine if ground-penetrating radar (GPR) could be used to detect hard pans. Hard pans were formed in two soils at two depths and with two different bulk densities. A penetrometer was also used to determine hard pan depth and for comparison with GPR. Correlations between hard pan depths predicted by each method were very linear and with correlation coefficients near 1.00. Future research could determine if this device can be used effectively in a wide range of soil types to detect hard pan depth and to determine soil density.

INTRODUCTION

Researchers and farmers alike recognize the detrimental effects of hard pans on crop growth. Hard pans contribute to poor rooting systems that can reduce crop yields (DeRoo, 1961; Simmons and Cassel, 1989; Campbell et al., 1974). Heavy field traffic and compaction resulting from tillage implements are the primary causes of hard pans. During the past several years, subsoiling has been used as one of the most effective methods of alleviating this compacted soil condition. A major problem with subsoiling is the energy that must be used to pull the subsoiler shanks through the soil. Larger and more powerful tractors must be used which, in turn, can increase the compaction problem. Tilling just deep enough to break up the hard pans is also important to avoid expending excessive energy.

The most widely used instrument for determining the location of hard pans is the cone penetrometer. Although it is a simple device, obtaining valid data with this instrument can be difficult. A significant problem is the amount of time that it takes to obtain accurate readings. The penetrometer must be inserted into the soil at each location that data is desired. This stop-and-go insertion method means that a continuous motion over the soil surface is not possible. The penetrometer can also be overly sensitive. The author has noted that large variations in penetrometer data can be obtained from field soil because of the presence of clods and crevices. Even in controlled conditions, such as in the soil bins at the NSDL, high variability can occur. Variables other than soil strength and soil nonuniformity can also influence the accuracy of the penetrometer's measurements. These include penetrometer insertion speed and the method used to obtain readings (whether the instrument is stopped at predetermined depth increments to obtain readings, or if the readings are recorded as the penetrometer is inserted in a continuous motion).

Another factor that must be considered in the use of the penetrometer is how accurately it can locate hard pans. For computer modeling of soil compaction, it is important to know the exact location of the hard pan. Errors of only a few centimeters can cause large variations in the indicated extent of soil compaction. Research has shown that the interpretation of cone index in typical layered field soils Is difficult (Mulqueen et al., 1977). Evaluating the plot of cone index vs. depth can prove to be misleading. In some soils, it has been reported that a wedge can build up in front of the cone (Gill, 1968). In this situation, it is plausible that the wedge could cause the hard pan to be prematurely sensed.

Because of the problems associated with the penetrometer and the need for another device to nondestructively and accurately locate the depth of hard pans, an experiment was designed to evaluate ground-penetrating radar (GPR) as a means of locating these hard pans. GPR systems can enable researchers to look into the soil for discontinuities or irregularities that otherwise might be hidden or difficult to detect without a shovel.

GPR technology was first developed in the early 1970s. The military was the first user (Greer, 1986; Pittman et al., 1984). Applications ranged from locating land mines to underground tunnels. Other applications of this technology have been to map river bottoms and determine thickness of ice (O'Neill and Arcone, 1988). Archaeologists have also used GPR to facilitate excavation strategies and determine the presence of underground objects (Doolittle, 1988). Another important research use of this device has been to determine the lateral extent and depth of subsurface features and their spatial variability on the southern coastal plain of Georgia (Truman et al., 1988). The depths of water tables have also been determined using GPR (Asmussen et al., 1986).

GPR is a broad band, impulse radar system that has been specifically designed to penetrate earthen materials (Doolittle, 1987). A short electromagnetic pulse (in the frequency range of 10-1000 MHz) is radiated into the earth from an antenna that is placed close to the ground. The

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pulses are reflected from the ground surface and from subsurface interfaces. The reflected signals are detected by a receiver unit located inside the antenna and the time interval between transmission and detection is recorded. The resulting data is then displayed on a continuous strip-chart recorder. Depending upon variations in the electromagnetic response of geologic materials, the depth to irregularities at depths of up to 25 m can be determined to a resolution of several centimeters.

Variations, accuracy, and maximum probing depth of GPR are influenced by the electrical parameters of the soil. The equation used by Geophysical Survey Systems, Inc. (GSSI) (1982) that governs the depth of penetration of GPR signals is

$$D = \frac{0.1524\ ct}{\sqrt{e_r}} \tag{1}$$

where

D = depth in meters,
c = velocity of light = 3×10^8 m/s,
t = pulse travel time in nanoseconds,
e_r = relative dielectric constant of material.

The principal factors influencing e_r are moisture content and the amounts and types of clays and salts present. Table 1 (GSSI, Inc., 1982) shows some of the variations in e_r for these and other materials.

To properly evaluate an instrument, it is important to vary the parameters that have the largest effect on it. The most significant parameters than can affect GPR are moisture content, clay amount, clay type, and salt content. No information about the salt content was available for the soils in the bins. This factor, however, as well as the clay content should remain constant within a soil type. When soil type is changed, dielectric constant of the material, salt content, and clay type are, in fact, also changed. Therefore, an experiment was designed in the soil bins at the NSDL that varied 1) soil type, 2) moisture content, 3) depth of hard pan, and 4) soil bulk density.

The objectives of this study were to:

1. Evaluate the potential for using GPR to determine the depth and density of hard pans in two soil types with different clay and moisture contents.
2. Correlate GPR measurements with penetrometer measurements.

METHODS AND MATERIALS

The GPR system used in this study was the SIR (Subsurface Interface Radar) System-8 manufactured by Geophysical Survey Systems, Inc. This system was equipped with a control unit, a graphic recorder, a Model 07/3 Power Distribution Unit, a Model 20P Remote Control Unit, a transducer/control cable, and the transducer (antenna and transmit/receive electronics). Power for the system came from a 12-volt automotive battery. A 500 MHz antenna was used for this study because of the increased resolution near the surface. This antenna cannot probe as deeply as 80 MHz, 120 MHz, or 300 MHz antennas but can provide more exact information near the surface.

TABLE 1. Dielectric constant of various-earth materials (GSSI, 1982)

Material	Approximate Dielectric Constant, e_r
Air	1
Fresh water	81
Sea water	81 - 88
Granite	8
Sand, dry	4 - 6
Sand, saturated (fresh water)	30
Silt, saturated (fresh water)	10
Clay, saturated (freshwater)	8 - 12
Average soil	12

Norfolk sandy loam soil and a Decatur clay loam soil were used for the experiment because their clay contents were quite different. The Norfolk sandy loam soil consisted of 71.6%, 17.4%, and 11.0% sand, silt, and clay, respectively. The Decatur clay loam consisted of 26.9%. 43.4%, and 29.7% sand, silt, and clay, respectively. Each soil's clay mineralogy was basically the same, with each having about 45% kaolinite and a substantial amount of the remainder vermiculite. Clay type, therefore, should have little effect on the experiment. Each soil probably also had little salt content in solution because of its current use in the soil bins, again minimizing its influence.

The soil bins at the NSDL offered the unique opportunity to place a hard pan at a particular depth and maintain that depth over all the bin area with small variation. The indoor soil bins offered the increased advantage of controlling moisture contents. Two depths were selected for the hard pans, and an experiment was planned that used the GPR to predict each depth. We also thought that it might be possible to determine the level of soil density that made up the hard pan. A single pass of a rigid wheel was used to create one soil density in the hard pan, and a second pass with the device was used to create a hard pan with an even higher density.

Each soil bin was split into two blocks (Fig. 1). Each block was split into four plots with two hard pan depth treatments and two hard pan density treatments. A hard pan was simulated by plowing out the soil nearest the surface and packing at an approximate depth of 25 cm or 40 cm using the rigid wheel with either one or two passes. The surface soil was then put back in the furrow and allowed to

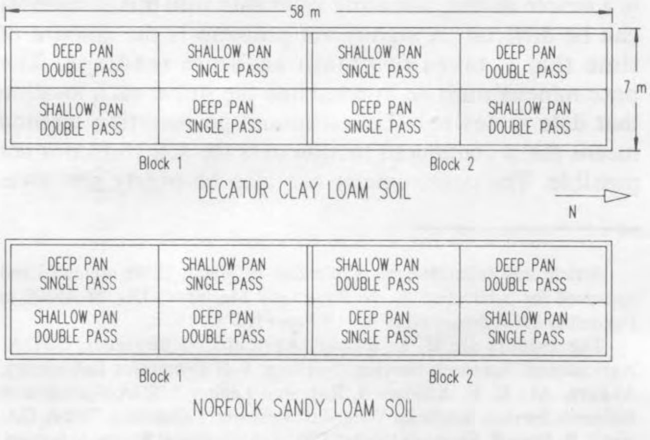

Figure 1–Experimental design of the NSDL indoor soil bins. The shallow and deep pan treatments refer to the depth of the hard pans relative to the soil surface. The single- and double-pass treatments refer to the number of passes that were made by the rigid wheel to form the hard pans.

sit in the bins for several weeks to equilibrate before testing.

Penetrometer readings were taken in the. soil bins with the NSDL penetrometer vehicle according to ASAE Standard S313.2 (ASAE, 1988) after the GPR measurements were completed. These readings helped to determine if the hard pan was placed at a consistent depth throughout a plot area. They also provided a base for comparison with the GPR depth measurements. Moisture content measurements were also taken at several depths at the conclusion of each portion of the experiment.

Substantial experimentation was required to determine the proper method of moving the antenna across the soil bins. To first determine if it was possible with the GPR to sense the hard pans, the 500 MHz antenna was simply dragged across the bin with a rope. The results indicated that the hard pans could be located. Two steel pipes were then buried in each bin parallel to the length of the soil bin and on top of the hard pan for depth calibration purposes. These pipes were then located with the GPR. In the analysis of the data, it became apparent that the GPR was masking the location of the shallow pipe (that was within 30 cm of the soil surface) with extraneous signals. To correct this, the antenna was suspended at an approximate height of 25 cm above the soil surface. This height permitted the successful location of the pipe closest to the soil surface.

The GPR antenna was then suspended beneath one of the soil bin vehicles. The metal pipes in the soil were then not able to be detected. The large metal frame of the car prevented the antenna, even though it was shielded, from detecting the underground objects. To isolate it from the vehicles, the GPR antenna was suspended from wood posts extending in front of the vehicle. The metal pipes could then be located. The GPR antenna was used in this position throughout the experiment.

RESULTS

The GPR was first used to obtain a set of measurements in each soil bin with the soil in a relatively dry condition. Moisture content results indicated that the Norfolk sandy loam soil and the Decatur clay loam soil had initial moisture contents of 6.7% and 12.6%. respectively, in their hard pans. A different moisture content treatment was obtained for each soil by wetting and allowing the soil to equilibrate to a uniform moisture content. Moisture content samples taken at the conclusion of the second set of GPR measurements showed the hard pans of the Norfolk sandy loam soil and the Decatur clay loam soil were at moisture contents of 8.0% and 14.3%, respectively.

Bulk density measurements were also taken from above, within, and below the hard pans in each plot. The density of the Norfolk sandy loam soil (Fig. 2) was increased within the pan relative to the overlying soil. Note the slight increase in bulk density of the hard pans with the double-pass treatment.

Bulk densities (Fig. 3) followed the same general pattern for the Decatur clay loam soil. However, this soil could also be more. difficult to analyze because of several factors. A problem could occur because the bulk density of the double-pass hard pan was not increased significantly over the bulk density of the single-pass hard pan. This very slight increase probably could not be distinguished through the use of GPR. Also note from Fig. 3 that the bulk density of the hard pan was lower in the shallow location than in the deeper location. This decrease could be due to the soil condition and the rigid wheel linkages not allowing as much pressure to be applied at the greater depths.

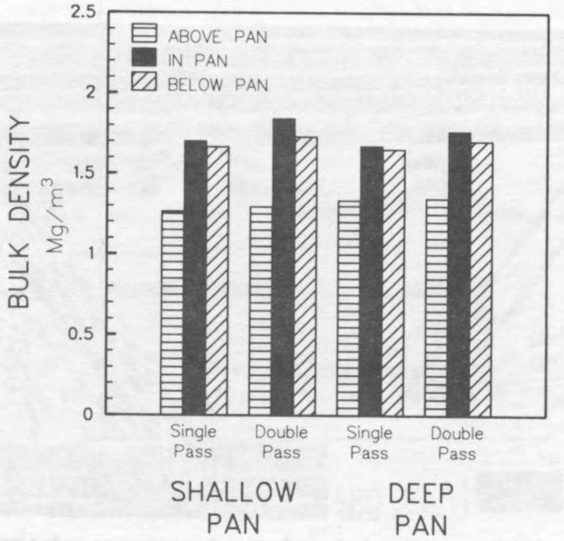

Figure 2–Bulk densities within Norfolk sandy loam soil bin.

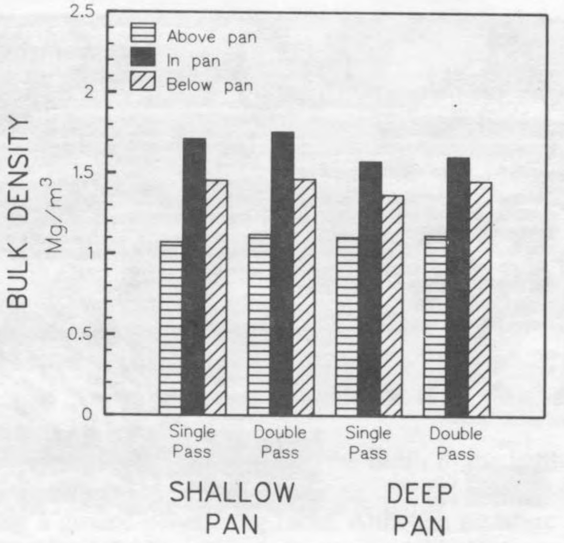

Figure 3–Bulk densities within Decatur clay loam soil bin.

Some interesting trends were noticed during the experiment. The output of the GPR showed that the metal pipes were located more clearly in the Norfolk sandy loam soil than in the Decatur clay loam soil, especially after wetting the soil (Figs. 4 and 5). The hard pans in the Norfolk sandy loam soil were also easier to locate. In the Decatur clay loam soil, a substantial amount of noise was noticed that made locating the hard pans more difficult. This noise was not only the result of the increased clay content, but also reflected the presence of large clods.

The data were scaled from the pipe depth information. For each moisture content and soil type, a new standard depth was determined from the appropriate set of pipe depth readings. The pipe located deeper in the soil was used for depth calibration because of the increased soil

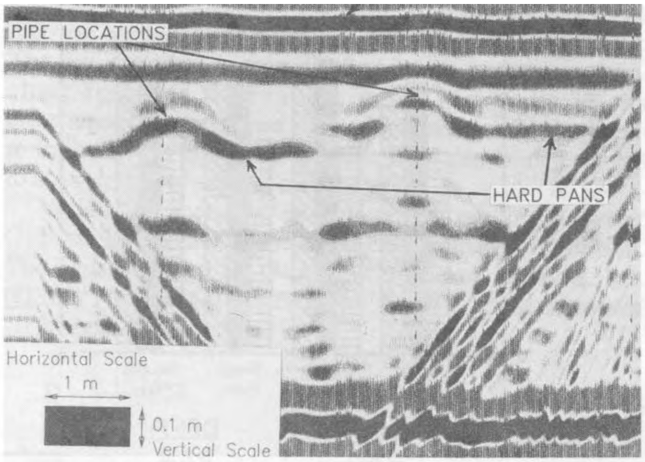

Figure 4–Cross-sectional view of ground-penetrating radar graph showing depth of the pipes in the Norfolk sandy loam soil when the soil was at 8.0% moisture content.

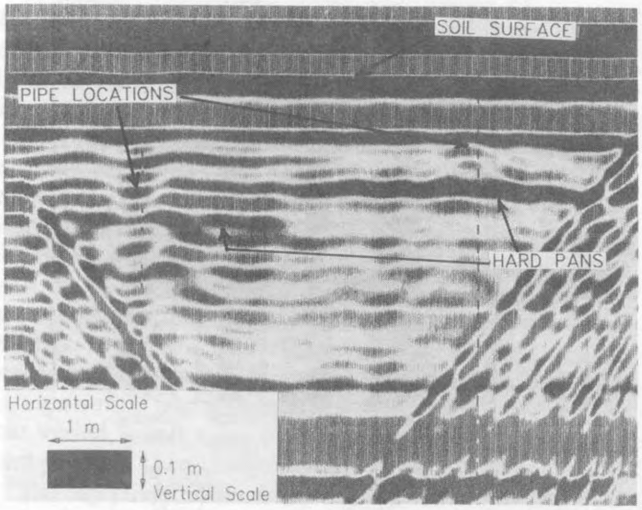

Figure 5–Cross-sectional view of ground-penetrating radar graph showing depth of the pipes in the Decatur clay loam soil when the soil was at 14.3% moisture content.

thickness above it. This increased depth should provide a better calibration because the top of the deeper pipe is between the depths of the installed hard pans. The top of the shallower pipe is located above both hard pans.

A typical cross-sectional GPR graph is shown in Fig. 6 for the Norfolk soil at 6.7% moisture content. The upper three gray bands are unimportant reflections. The upper black band on the graph is thought to be the reflection of the signal when it hits the 25 cm of air. The second black band is the soil surface. The hard pan is the next extremely dark band. The different depths of the two hard pans across the bins can be seen on the GPR graph. Also note the difference in the gray scales of the hard pans. The shallower pan on the tight was created with one pass of the compacting device. The deeper pan on the left was created with two passes of the compacting device. The dark lines running at about a 45-deg angle down towards the center of the bin are reflections from the bin walls. In some of the graphs, the tiller pan is observed. This is the deepest depth that the equipment at the NSDL can till the soil. This pan has been created after many years of use of the upper portion of the soil while leaving this deeper portion undisturbed.

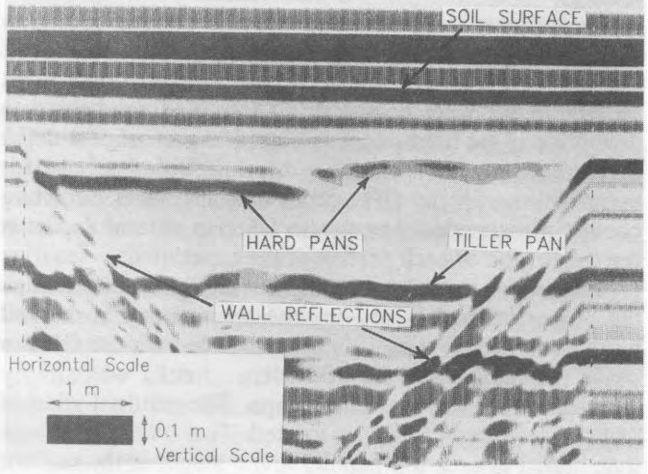

Figure 6–Typical cross-sectional view of ground-penetrating radar graph showing the depths of the hard pans in the Norfolk sandy loam soil when the soil was at 6.7% moisture content.

Six locations in each plot were measured with the penetrometer down to almost 80 cm to determine the death of the hard pan. These data were then analyzed to determine the depth that the maximum cone index reading was obtained. The hard pan was assumed to start at the depth that this peak reading occurred. At the same cross-sectional position on the GPR graphs, the depth to the hard pan was measured and directly correlated with this penetrometer measurement.

The GPR data and the penetrometer data were first analyzed for significant interactions that could affect the result of the experiment. The GPR data showed that the means obtained from each soil type were not statistically different (Table 2). But the penetrometer data showed this

TABLE 2. Average hard pan depths determined by GPR and penetrometer

Soil*	Depth†	n‡	Mean	SD §
			GPR	
D	1	48	28.3	3.0
D	2	48	39.4	3.9
N	1	48	28.7	1.9
N	2	48	38.3	4.0
			Penetrometer	
D	1	48	23.8	2.0
D	2	48	33.2	5.9
N	1	48	29.4	1.8
N	2	48	38.2	1.9
			Difference	
D	1	48	4.5	2.5
D	2	48	6.2	4.2
N	1	48	-0.7	1.8
N	2	48	0.1	3.5

*Soil = D is Decatur clay loam soil
= N is Norfolk sandy loam soil

†Depth = 1 is shallow installed hard pan
= 2 is deep installed hard pan

‡n is the number of samples.

§SD is standard deviation.

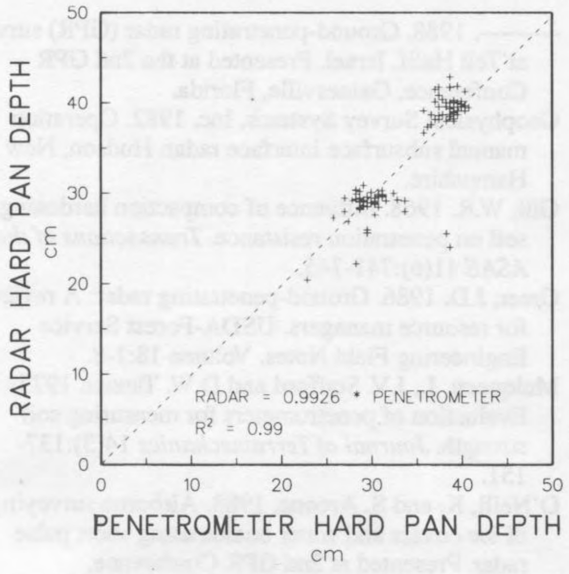

Figure 7–Hard pan depth predicted by ground-penetrating radar plotted against hard pan depth predicted by penetrometer for Norfolk sandy loam soil.

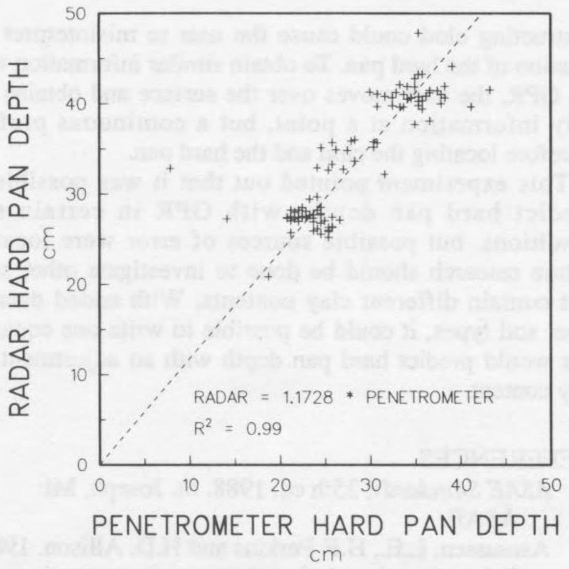

Figure 8–Hard pan depth predicted by ground-penetrating radar plotted against hard pan predicted by penetrometer for Decatur clay loam soil.

factor to be highly significant (1% confidence interval). Based on the discrepancies, the data set from each soil type were analyzed separately. This was an expected result. We did not expect to determine one equation that would be valid for all soils.

Analyzing the GPR data by soil type showed that moisture by itself was not a significant factor. This was a surprising result because Table 1 indicates water could have the greatest effect on the capability of the GPR to determine depth of the hard pan. One reason for this result could be the relatively small difference in moisture content despite significant differences in soil appearance, penetration resistance, and ability to read the GPR output. The only other factor in this analysis that proved significant was the depth factor. This was reasonable, because the depth that the hard pan was installed should influence where the penetrometer and GPR detected it. Similar analyses were conducted on the differences between the paired measurements of GPR and penetrometer at each location and this resulted in no new information.

Because the data showed that the only significant interaction occurred because of the difference in soil type, the next step was to directly compare the depths of hard pans predicted by GPR and penetrometers. No justification supports incorporating moisture into the final analysis.

Figures 7 and 8 show the depth predictions of GPR plotted against the depth predictions of the penetrometer for each soil type. The line drawn through the data is the linear fit of the data with the origin forced to be at zero. Each line provided a very good fit of the data with the R^2 being close to 1.00 each time. The GPR predictions closely matched the penetrometer predictions for the Norfolk sandy loam soil with the slope of the line also being very close to 1.00. Data from the Decatur soil indicated that the slope for this soil was slightly greater, being 1.173. But again the linear prediction equation fit the data closely.

At this time there is inconclusive evidence that the relative density of the hard pans can be predicted from ground-penetrating radar. In some instances (Fig. 6) a clear visual difference exists between the two densities of the hard pans. In other situations, this difference is not as extreme. Further complications could occur because of the type of data being analyzed. The thermal printer that produces the GPR gray-scale graphs is subject to environmental changes and could alter the graphs' relative grayscales. The data should be stored in digital form and the graphs produced in a constant temperature, constant humidity, etc. environment. An imaging system could then be used to determine if the gray scales for the lesser density hardpans differ significantly from the gray scales for the greater density hard pans.

CONCLUSIONS

This experiment showed that the depth of the hard pan in two soils at the NSDL could be closely predicted by using a ground-penetrating radar. Although moisture had been thought to be a very important variable in the use of this device, different moisture contents when moisture was uniform throughout the soil profile didn't affect GPR results. However, the presence of a wetting front and moisture bands could complicate the use of GPR. Soil moisture near field capacity could also provide problems, but the soil probably would not be trafficable to obtain GPR readings under this condition.

GPR was used successfully to predict the depth of hard pan in the Norfolk sandy loam soil. This success was probably due in part to this soil's low clay content (11.0%). A 1:1 correlation between the depth predictions of the GPR and the depth predictions of the penetrometer was found. Accurate predictions of hard pan depth were also obtained in the Decatur clay loam soil that had a clay content of 29.7%. Although a linear relationship was possible and very close approximations were possible, the slope between the GPR and the penetrometer hard pan depth predictions was 1.173.

Significant distinctions between the use of GPR and the penetrometer bears mentioning again. To obtain information about a soil condition with a penetrometer, the user must stop and insert the probe into the soil. An obstructing clod could cause the user to misinterpret the location of the hard pan. To obtain similar information with the GPR, the user moves over the surface and obtains not only information at a point, but a continuous profile, therefore locating the clod and the hard pan.

This experiment pointed out that it was possible to predict hard pan depths with GPR in certain soil conditions, but possible sources of error were located. Future research should be done to investigate other soils that contain different clay contents. With added data on other soil types, it could be possible to write one equation that would predict hard pan depth with an adjustment for clay content.

REFERENCES

ASAE Standards, 35th ed. 1988. St. Joseph, MI: ASAE.

Asmussen, L.E., H.F. Perkins and H.D. Allison. 1986. Subsurface descriptions by ground-penetrating radar for watershed delineation. Georgia Agricultural Experiment Station Research Bulletin 340.

Campbell, R.B., D.C. Reicosky and C.W. Doty. 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. *J. Soil. Water Conserv.* 29(5):220-224.

DeRoo, H.C. Deep tillage and root growth. 1961. Connecticut Agricultural Experiment Station Bulletin 644.

Doolittle, J.A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. In *Soil Survey Techniques,* 1l-32. Soil Science Society Special Publication Number 30.

----. 1988. Ground-penetrating radar (GPR) survey at Tell Halif, Israel. Presented at the 2nd GPR Conference, Gainesville, Florida.

Geophysical Survey Systems, Inc. 1982. Operation manual subsurface interface radar. Hudson, New Hampshire.

Gill, W.R. 1968. Influence of compaction hardening of soil on penetration resistance. *Transactions of the ASAE* 11(6):741-745.

Greer, J.D. 1986. Ground-penetrating radar: A review for resource managers. USDA-Forest Service Engineering Field Notes. Volume 18:1-8.

Mulqueen, J., J.V. Stafford and D.W. Tanner. 1977. Evaluation of penetrometer for measuring soil strength. *Journal of Terramechanics* 14(3):137-151.

O'Neill, K. and S. Arcone. 1988. Airborne surveying of ice covers and water bodies using short pulse radar. Presented at 2nd GPR Conference, Gainesville, Florida..

Pittman, W.E., Jr., R.H. Church, W.E. Webb and J.T. McLendon. 1984. Ground penetrating radar, a review of its applications in the mining industry. U.S. Bureau of Mines Information Circular 8964.

Simmons, F.W. and D.K. Cassel. 1989. Cone index and soil physical property relationships on a sloping Paleudult complex. *Soil Sci.* 147(1):40-46.

Truman, C.C., H.F. Perkins, L.E. Asmussen and H.D. Allison. 1988. Using ground-penetrating radar to investigate variability in selected soil properties. *J. Soil. Water Cons.* 42(4):341-345.