ERDC/CRREL LR-04-37

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Evaluating the Capability of Ground-Penetrating Radar To Define Tree Roots and Cracks in Concrete Walls

A. Palazzo, N. Yankielun, L. Gatto and T. Cary

September 2004

Approved for public release; distribution is unlimited.

ERDC/CRREL LR-04-37
September 2004

Evaluating the Capability of Ground-Penetrating Radar To Define Tree Roots and Cracks in Concrete Walls

A. Palazzo, N. Yankielun, L. Gatto and T. Cary

Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, New Hampshire 03755

Approved for public release; distribution is unlimited

Prepared for U.S. Army Environmental Center

DISCLAIMER: The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Evaluating the Capability of Ground-Penetrating Radar To Define Tree Roots and Cracks in Concrete Walls

A. Palazzo, N. Yankielun, L. Gatto and T. Cary
Cold Regions Research and Engineering Laboratory
Engineer Research and Development Center
72 Lyme Road
Hanover, New Hampshire 03755

ABSTRACT

The Army Environmental Center (AEC) funded CRREL to determine if a ground-penetrating radar (GPR) can locate plant roots and measure root depth to help decide if trees should be allowed to grow on earth-covered magazines (ECMs). We conducted three experiments to test how well GPR can detect individual and networks of roots of mature pine trees, define different known-dimensioned targets composed of wood and steel, and detect gaps in concrete wherein tree roots may grow. We used a commercially available *SIR-2000* GPR system and a 1.2 GHz antenna. Our results show that GPR can detect wood buried in soil. The likelihood of detection improves as the diameter of the wood target increases and the depth decreases. Our experiments suggest that GPR could neither differentiate a dead, dry tree root from a living root of similar diameter nor detect the presence of vertical cracks and root intrusions into the roof of an ECM when the GPR antenna was dragged across the overburden on an ECM. However, it is probable that GPR could detect cracks in concrete when used along the inside walls and ceiling of an ECM. Future experiments could help define some of these capabilities.

Keywords: Ground-penetrating radar (GPR), tree roots, concrete cracks

1.0 INTRODUCTION

1.1 Background

The Army Environmental Center (AEC) funded CRREL to conduct GPR experiments to determine if a GPR can locate plant roots and measure root depth as part of the project "Evaluating the growth of trees on earth-covered magazines." The results of this research can be used to help determine if trees should be allowed to grow on earth-covered magazines (ECMs). Trees on ECMs would reduce annual mowing costs, earn forestry dollars, and better conceal the ECMs from air observations.

However, a major concern about trees growing on ECMs is whether or not the tree roots can grow into and widen existing cracks and penetrate the concrete roofs of the ECMs, which would compromise their structural integrity and allow water to seep into the storage building. There are a least 17 facilities in climate regions that support tree growth. If GPR can be used to detect tree roots and root penetration into cracks in concrete walls, then it could be used to monitor whether or not tree roots have penetrated into the concrete-wall roofs of ECMs without having to strip the soil cover from ECMs to make a visual determination.

1.2 Previous Research

Ground-penetrating radar is an electromagnetic imaging technique that can be used to detect buried objects or hidden structures. It has been used for geological research, archaeology, forensics, and assessment of the integrity of concrete structures such as roads and bridges. U.S. Forest Service researchers recognized the potential for using GPR technology to detect tree roots and estimate root biomass rapidly and noninvasively (Butnor et al., 2001). Estimating root biomass traditionally involves taking soil cores or digging pits, which are destructive, labor-intensive, and not very useful for measuring the lateral extent of a root system. Butnor and others (2003) used advanced GPR signal processing techniques and calibrated the results with soil core data to demonstrate that GPR can be a powerful, cost-effective tool to measure root biomass where site conditions are favorable.

The capability of GPR to detect subsurface objects including roots is dictated by the electromagnetic properties of the soil and the target objects being surveyed (Doolittle et al., 2002). Electrically resistive soils, i.e., high sand content, are more amenable to GPR surveys than conductive soils. Soil moisture also affects radar-wave penetration into a soil. The difference between the moisture in a target and that in the surrounding soil also affects the ability of radar to

differentiate objects. A soil with many variably sized objects of different composition will clutter a radar signal trace and complicate the ability of the interpreter to differentiate and characterize subsurface objects. Radar-signal-processing techniques can improve some of these interpretations by enhancing the targets of interest (Daniels, 1996).

2.0 Experiments

2.1 Objectives

Our overall goals were to expand on current knowledge of GPR capabilities to differentiate plant roots from other objects and to develop new knowledge regarding capabilities to detect cracks in concrete. This latter goal was established so as to evaluate how GPR may serve to detect tree-root penetration into concrete structures such as ECMs. In our experiments we used a commercially available 1.2 GHz GPR to evaluate 1) how well it could detect and differentiate targets of known size and composition placed at different orientations and depths, and 2) its capability to detect cracks in concrete. These evaluations have not been done previously.

2.2 Experiments at Hanover Golf Course

2.2.1 Rationale and Setup

The Hanover, NH, golf course provided a simplified environment where we could choose locations with individual trees or small stands of trees for GPR testing that were far less complex than a heavily forested area where we would have little to no control of root density. These initial experiments were conducted in October 2003 at three sites: 1) old, unused, bentgrass green; 2) a stand of living, white pine trees; and 3) a sand trap. Each site had sandy soil, which is a favorable medium for GPR surveying. We selected the old, which was a large area of open grass where no tree roots would exist green, as a control site. The pine trees had extensive, near-surface individual roots and root networks and were ideal for determining if GPR was capable of detecting live roots. The sand trap provided a site with a grass surface and a sand surface with no underlying tree roots.

2.2.2 GPR Data Collection

The GPR data were collected using a commercially available *SIR-2000* ground penetrating radar system and an associated 1.2 GHz antenna (GSSI, North Salem, NH) (Fig. 1). The system was set up to collect 32 radar scans per second of 16-bit resolution data with 1024 data points per scan. Radar parameters were set to provide a maximum round-trip pulse travel time of 10 ns. If an estimated soil dielectric constant of 5 is assumed, that travel time translates to a maximum

penetration depth of 68 centimeters. With this system, the data could be viewed in real time, although additional post-processing tends to improve visualization.

The collected radar data were processed on a laptop computer using *RADAN* (GSSI, North Salem, NH) software. Only the most rudimentary post-processing enhancement was performed. It consisted of "stacking" (or computing running averages) of several adjacent radar scans to improve the signal-to-noise ratio and more clearly display the details.

Figure 1. SIR-2000 GPR system (left) and associated 1.2 GHz antenna (red box on right).

2.2.3 Results and Discussion

2.2.3.1 Green

The GPR antenna was dragged over an unused green (Fig. 2) located far enough from trees to ensure that no living roots where in the soil. The GPR trace from this green (Fig. 3) is quite uniform showing very few in-soil reflectors, which are indicated by inverted V- or U-shaped features. Such reflectors can be roots, rocks, or other objects with a density or a dielectric constant or both that is very different from that of the surrounding soil. The absence of such reflectors suggests that the soil under this green is rock and root free.

Figure 2. The antenna was dragged for 12 meters along the tape across the surface of a golf green composed of creeping bentgrass.

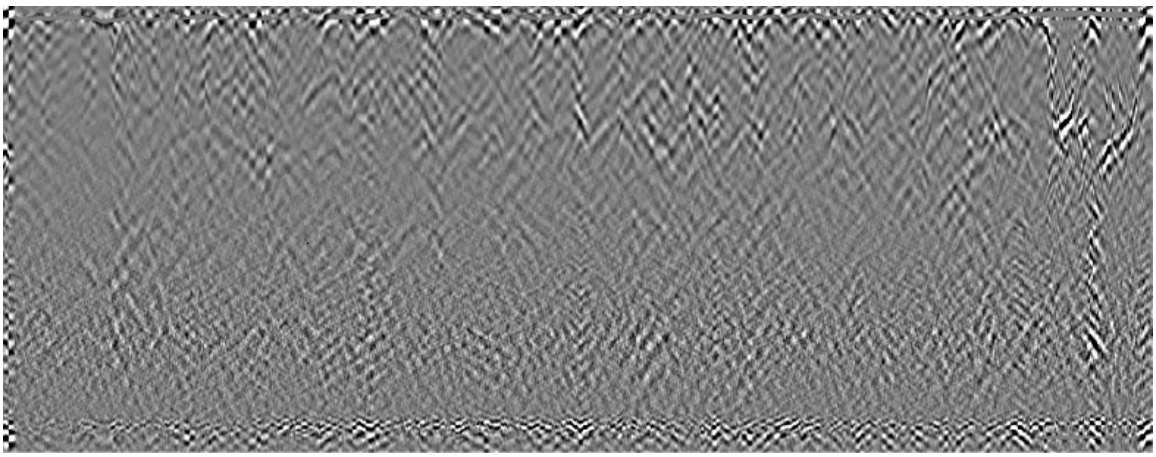


Figure 3. GPR trace of the green.

2.2.3.2 Trees

The GPR antenna was dragged over the ground along a 15-m line laid through a stand of eight white pine trees (Fig. 4). Here numerous inverted V- shaped features are present along the GPR trace near the surface and at depth (Fig. 5). Some of these features are no doubt from the individual roots that make up the dense networks of near-surface, roots from the eight trees; and, some might be from rocks in the soil. While we detected these tree roots, we were not permitted to excavate and measure root diameters and depths to correlate with the radar features.

Figure 4. The antenna was dragged for 15 m only the ground amongst eight trees. Trees were 0.3 to 1.5 m from the antenna and were 73 to 190 cm in diameter at breast height.

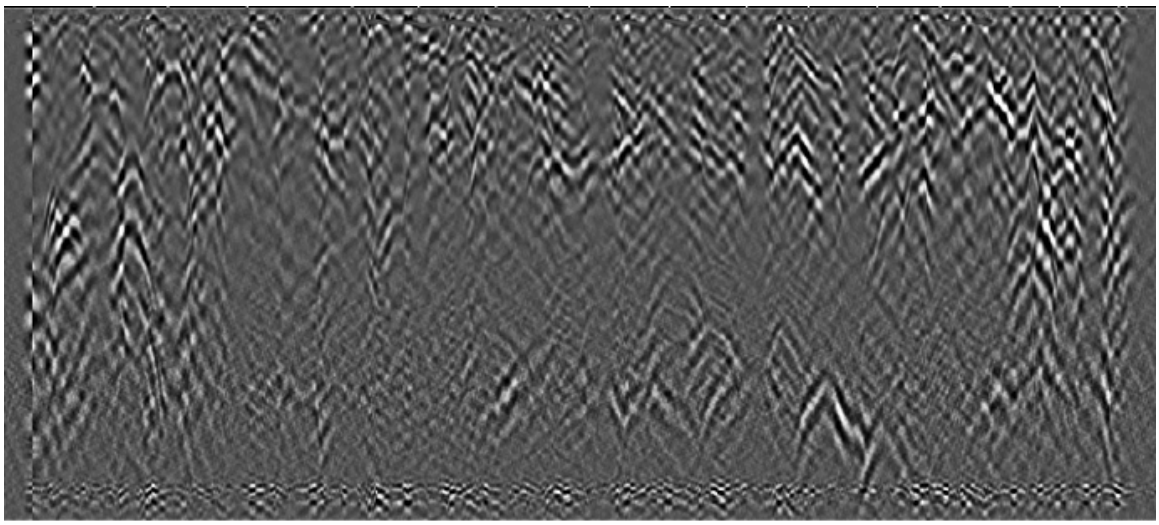


Figure 5. GPR trace amongst the white pines.

2.2.3.3 Trap

The GPR antenna was dragged over the ground along a 15-m line (Fig. 6) that started on grass on one side of the trap, went through the trap, and continued back onto grass. Where the

antenna passed over grass at the extreme left and right of the GPR trace, V- or U-shaped features are nearly absent suggesting that the soil is free of roots and rocks like the soil under the old green (Fig. 7). However, when the antenna was on the sand trap a wavy linear feature is visible near the top of the trace. This feature abruptly ends at the grass-trap boundaries. This strong horizon indicates the boundary between the bottom of the sand trap and the underlying, denser soil. The features below this horizon are of unknown origin, although we believe they may be tiles from a drainage system or trees roots that remain beneath the sand trap. This trap is part of a new golf hole that was constructed in a wooded area two to three years ago, so roots from the removed trees could still be in the soil.

Figure 6. The GPR antenna was dragged for 15 m from the grass on one side to a sand trap, through the trap, and unto the grass on the other side.

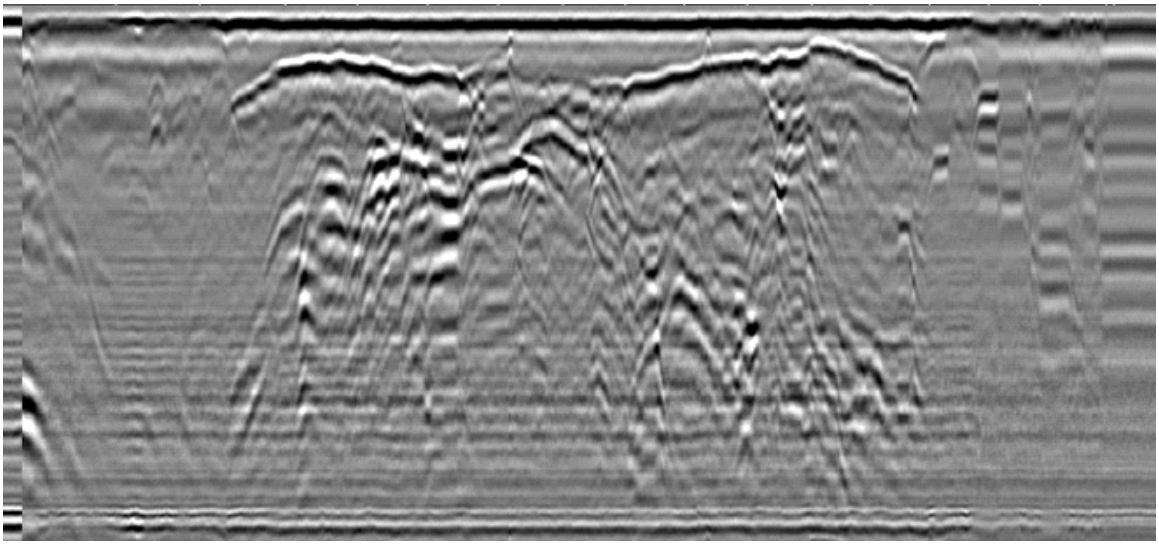


Figure 7. GPR trace across the sand trap.

2.3 Experiments at CRREL

2.3.1 Rationale and Setup

Based on the results of the experiments on the golf course where we could clearly see roots but could not determine their size and depth, we designed follow-on experiments to explicitly test the hypothesis that GPR can differentiate the composition, depth, diameter, and orientation of targets in soil. Our second hypothesis was that GPR can detect cracks in concrete walls and tree roots growing in them. To test these hypotheses, we conducted experiments in August 2004 in a CRREL test cell, which contained a uniform Charlton fine loam soil similar to the sandy soil on much of the Hanover golf course.

2.3.1.1 Test One

We selected targets made of three materials: freshly harvested white-pine stems to represent live tree roots, kiln-dried wooden dowels to represent dead tree roots, and steel pipes to serve as a calibration marker. The pine and dowel targets were selected because living and dead tree roots are the two primary targets that must be detected to evaluate whether or not tree roots have invaded the cracks in ECMs.

The moisture content of targets affects their dielectric constant, which in turn affects how readily a target reflects a radar signal. Targets in soil that have very different moisture contents

than the surrounding soil will show up well. In general, large differences produce clear radar signals. The steel pipes had no moisture but had a very different dielectric constant than the soil. The kiln-dried wood was drier than the freshly harvested white-pine wood. The pine stems were used fresh for the experiments; they were dried after the experiments to determine there moisture content. We followed the suggestion of Fisher and others (2002) and dried the pine stems at 60°C until the mass of the stems was constant, i.e., no more water was being expelled during drying.

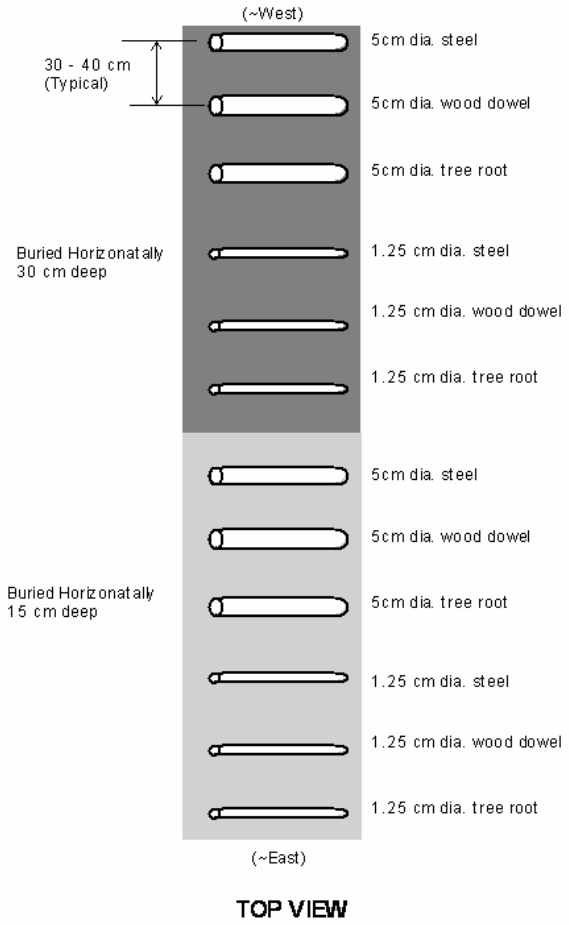
Each type of target was in two diameters: approximately 5 cm and 1.3 cm. Figure 8 shows the relative sizes and general appearance of the targets. We excavated a trench to make a soil surface free of vegetation and rocks. The bottom of the trench was undisturbed. We selected two depths to bury the targets, 15 and 30 cm, and two orientations, horizontal and 45°. The horizontal targets were placed in a row along the southern half of the trench, the 45° targets in a row on the northern half. Half the targets in each row were 30-cm deep, half were 15-cm deep. The rows of targets were about 45 cm apart. We laid the 30-cm-deep horizontal targets flat on the bottom of the trench and pushed the 30-cm-deep 45° targets into the bottom of the trench so they made a 45° angle with the bottom of the trench (Fig. 9).

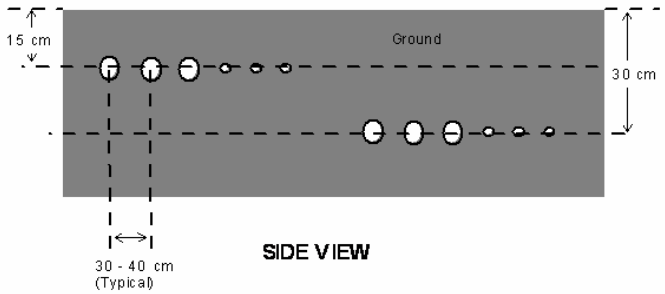
Figure 8. Targets used in the CRREL experiments, 5-cm targets in the lower half of the picture, 1.3-cm targets in the upper half. White pine stems were harvested 2-3 hours before the experiments.

Figure 9. 30-cm deep targets (bottom of each picture) were placed on the bottom of the trench, 15-cm deep targets (top) where placed on a 15-cm-high berm built on the bottom of the trench.

Then we built up a 15-cm high berm of soil on the bottom of the trench along the second half of each row. We placed a second set of targets on top of this berm (Fig. 9), the horizontal set of targets was laid flat on the top of the berm, the 45° targets were pushed into the berm. We then covered each row of 12 targets with soil so that each row had six targets buried 15-cm deep and six buried 30-cm deep. The schematics in Figures 10 and 11 show the target placement looking down on the top of each row and at the side and end.

Figure 10. Each row of targets was placed in the order shown here. The GPR antenna was pulled over each row from east (bottom) to west (top).





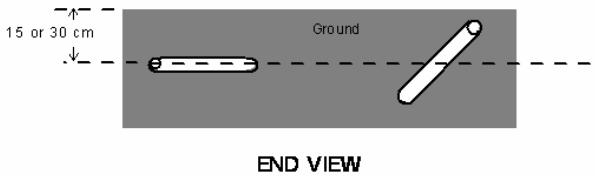


Figure 11. Side and end views of each row of targets.

2.3.1.2 Test Two

We used a poured-concrete, double wall that divided adjacent test cells for the test to detect cracks in concrete. The wall had a 20-cm thick, poured-concrete wall, a 2-cm space, and another 18-cm thick concrete wall (Fig. 12). The space appeared to be sealed with tar or some caulking agent. Both walls contained regularly spaced rebar, many of which were visible on the top surface of the walls. The top 61 cm of a vertical side of this double wall was exposed and used to do the GPR profile. The 2-cm space, which served as an analog for a large crack, had three small bushes growing in it at one location. The eastern most bush was 1.3-cm in diameter and was about 7.5 cm away from the other two. These two were 1.3-cm and 2.0-cm in diameter and extended along the space about 5 cm.

Figure 12. Top view (left picture) of the concrete wall. Side view (right picture) of the wall showing the exposed vertical side along which the GPR antenna was moved from left to the right of the bushes.

2.3.2 GPR Data Collection

We used the same radar hardware and setup as for the golf-course experiments. For test one, we marked the location of each target on the side of the trench (Fig. 13) and dragged the GPR antenna three times along the soil surface over each row of targets. When dragging the antenna we kept it in full contact with the soil at all times and pulled it at a constant rate as best we could.

Minimizing gaps between the antenna and soil is important because gaps complicate the GPR trace and produce confusing radar signals. The beginning and the end of each GPR profile is marked on the top of the traces in figures 14-16 with a pair of thin, white, dashed vertical lines on the left and right. The intermittent single dashed lines on these figures were made approximately every 50 cm along the profile lines.

Figure 13. Looking across the trench with the horizontal targets on the left and 45° targets on the right. Target locations were marked with orange paint on the side of trench, the berm was marked every 50 cm. The antenna was dragged over the target along the tape in the right picture. Tic marks were put on the GPR trace every 50 cm.

For test two we moved the antenna laterally along the exposed vertical side of the wall (Fig. 12) starting about 61 cm west of the bush and ending about 61 cm east of it while maintaining good contact with the wall at all times. The single vertical dashed line near the top of the center of the trace in Figure 16 indicates the approximate position of the small shrub stem and roots in the space.

2.3.3 Results and Discussion

2.3.3.1 Test One

The moisture of the white-pine stems (Table 1) in the 45° row was similar to that of the surrounding soil (Table 2) but somewhat drier than the soil in the horizontal row. The soil surface over the 45° targets sloped slightly to the south, facing the sun more than the soil surface over the horizontal targets, which dried out the soil around the 45° targets more than the soil around the horizontal targets. This moisture difference between the pine stems and soil could explain why the 45° targets appear less distinct than the horizontal targets.

Moisture Content (% by volume) of White Pine stems

Sample[1]	% Water/13.75cc[2]
1	5.7
2	5.9
3	5.2
4	6.6
5	5.8
6	7.7
7	7.1
	Ave = 6.3
	Std Dev = 0.9

Notes: 1) Seven sections of the pine stems were weighed and their volume measured, dried at 60C for seven days and weighed again to calculate the moisture content.
2) 13.75cc is the volume of the soil moisture sample.

Table 1. Volumetric moisture of the pine stems

GPR Target-Detection Experiment

Soil moisture (% by volume) measured 1610 hrs, 2 August 2004

South target line (north-facing side) (west to east) (horizontal targets)	North target line (south-facing side) (east to west) (45 deg targets)	Middle path (level) (west to east) (between target lines)	North side pile (top; variable density) (east to west) (out of trench)	South side pile (top; variable density) (west to east) (out of trench)
7.3	8.7	9.6	10.2	7.4
5.0	7.0	9.9	6.6	10.2
9.1	5.4	9.9	5.7	11.4
11.0	3.7	9.9	9.9	12.4
				14.0
8.1	6.2	9.8	8.1	11.1
2.6	2.1	0.2	2.3	2.5

Notes: 1) The Delta-T ThetaProbe type ML2x probe measures moisture in 13.75 cc of soil. If the soil density in sampled soil is not the same, the amount of water can vary between samples only because of the density difference.
2) The bottom two numbers in each column are the column average and standard deviation, respectively.

Table 2. Volumetric soil moisture.

Figure 14 shows the GPR trace of the horizontal targets, and Figure 15 shows the 45° targets. Both traces show some dominant patterns, inverted V- and U-shaped features, a dark upper zone above about 30 cm, and a light lower zone below 30 cm. The apex of each of the V- and U-shaped features is the location of one of the buried targets; there are no rocks in this soil. The boundary between the dark and light zones is the bottom of the trench.

The bottom of the trench is a significant density-difference boundary, which shows up well because the soil below the trench was undisturbed and denser than the soil that was backfilled around the targets above the bottom of the trench. The lighter colors (white, gray, yellow) below represent higher intensity of radar signal reflections from the denser-soil below. All the targets rest upon and are above the bottom of the trench surrounded by less-dense backfill, which produces less radar reflection than the denser soil below.

Most of the 15-cm targets buried horizontally and at 45° were more easily detected than the 30-cm targets because of the location where the 30-cm targets were placed rather than because of the greater depth of burial. The 30-cm deep targets lie on the denser soil at the bottom of the

trench and their signatures were likely somewhat “lost” in the radar reflections from that density boundary between the loose backfill and the dense soil below.

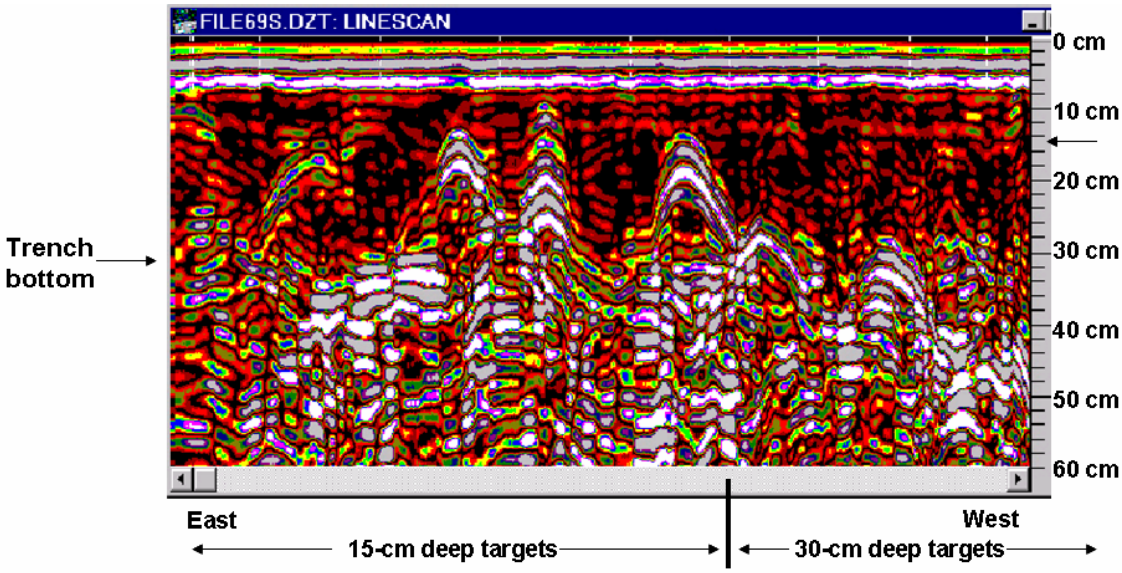


Figure 14. GPR trace of horizontal targets.

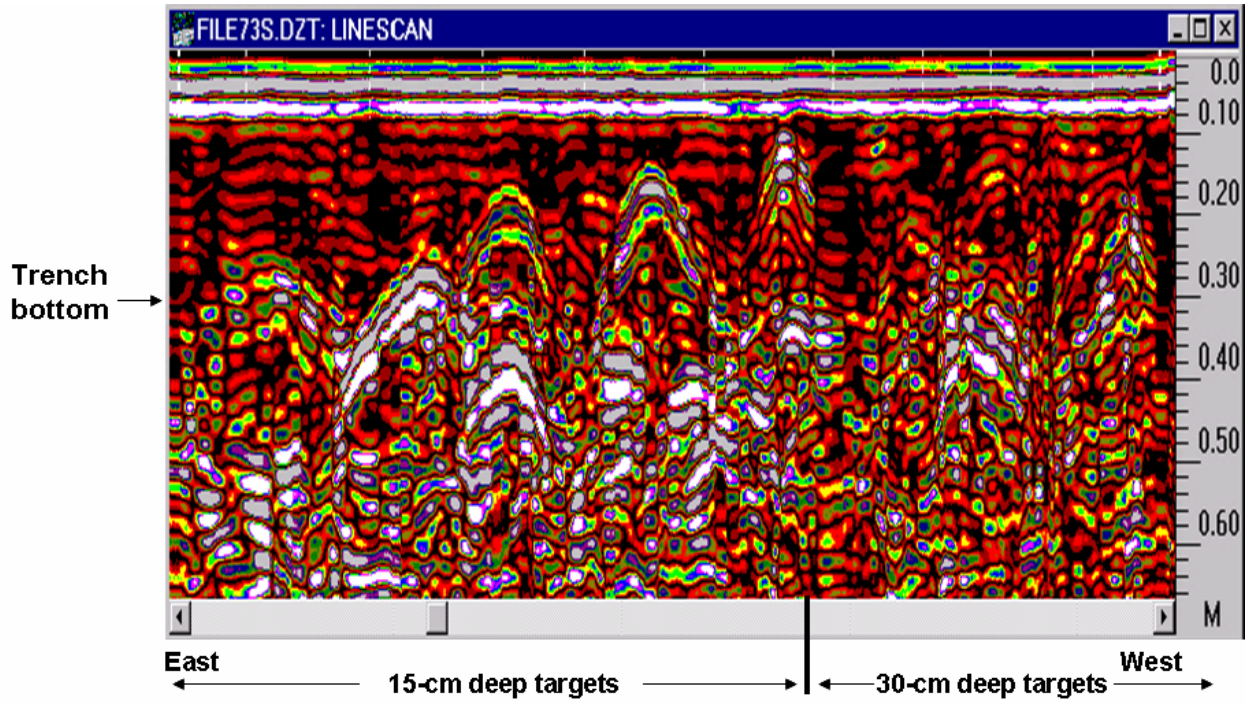


Figure 15. GPR trace of 45° targets.

In general, the 45° targets at 15 and 30 cm were less detectable than the horizontal targets. This may be because the horizontal targets provided a surface for direct return of the radar signal while the angled targets may have deflected the signal away from antenna. The GPR barely detected the 1.3-cm diameter targets of any material in either row, but the 5-cm targets of all the materials at 15-cm depth were detected. The steel tube was the mostly readily detectable target because it's composition and density contrast most with the surrounding soil.

2.3.2.2 Test Two

The GPR trace of the double wall with bush (Fig. 16) shows several features. The surface of the near wall, along which the antenna was moved, appears as the bright horizontal band at the top of the trace. About midway down, a horizontal pair of bright lines indicates the 2-cm wide space between the two walls. The rebars in the wall against which the GPR antenna was in contact are visible as the bright, inverted, V- and U-shaped features above the space on the trace. The rebars in the farther wall, i.e., below the space, are far less defined although additional signal processing of the radar data might reveal the rebar in that wall as well.

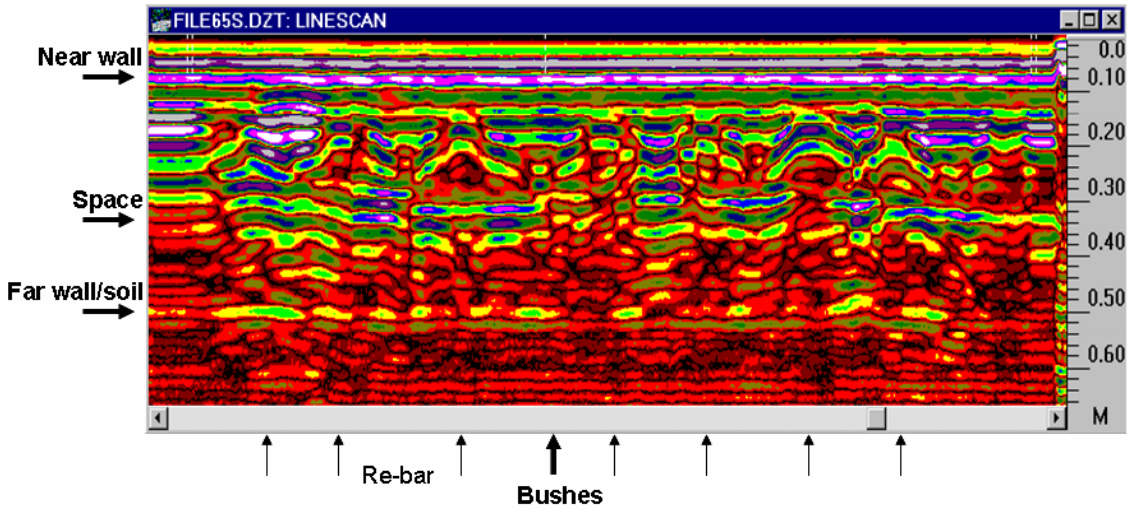


Figure 16. GPR trace of the double wall with bush.

The far side of the second wall, which is against soil, appears as a fainter horizontal line near the bottom of the trace. This interface does not present as strong a radar reflection as that from the near wall and the space between the walls. This is because the low electromagnetic (dielectric) contrast between the concrete and soil at the far wall.

The bushes in the space are practically undetected, although a bright spot is apparent in the space where the tic mark (the thin, white vertical line at the top of the trace) indicates the antenna passed the bushes. However, if one was using GPR to find roots in concrete cracks without prior knowledge of the locations of those cracks or the presence of roots in them, it is highly unlikely that the GPR as configured for these experiments would provide a distinct enough signature to readily show the roots. However, this trace suggests that cracks in concrete, if sufficiently wide, could be detected with the GPR used here.

3.0 Conclusions

These experiments confirm that GPR can detect wood buried in soil. The likelihood of detection improves as the diameter of the wood target increases and the depth decreases. However, it is not clear that a dead, dry tree root could be discerned from a living root of similar diameter.

We do not have sufficient data to draw a definite conclusion, but it appears that GPR would likely detect cracks in concrete that are 2-cm wide or more and that are oriented perpendicular to the radar signal. If such cracks existed in the roof of an ECM they would likely be detected by dragging a GPR antenna along the inner surface of an ECM roof. However, it is unlikely that roots that have intruded into such cracks would be detected by GPR, and it would therefore not be possible to determine if those cracks were formed by root intrusion. Future experiments could help define some of these capabilities.

We cannot say whether cracks in the roof of an ECM could be detected by doing a radar survey along the surface of the soil overburden on an ECM. We did not investigate that in these experiments. GPR surveys along the inside walls and roof of an ECM may be a viable means to detect the presence of cracks in the concrete structure.

4.0 References

Butnor, J.R., J.A. Doolittle, L. Kress, S. Cohen, and K.H. Johnsen. 2001. Use of ground-penetrating radar to study tree roots in the southeastern United States. Tree Physiol., 21:1269-1278.

Butnor, J.R., J.A. Doolittle, K.H. Johnsen, L. Samuelson, T. Stokes, and L. Kress. 2003. Utility of ground-penetrating radar as a root biomass survey tool in forest systems. Soil Sci. Soc. Am. J., 67:1607-1615.

Daniels, D.J. 1996. Surface-penetrating radar. The Institute of Electrical Engineers, London, U.K.

Doolittle, J.A., F.E. Minzenmayer, S.W. Waltman, and E.C. Benham. 2002. Ground-penetrating radar soil suitability map of the conterminous United States. Proceedings of SPIE – The International Society of Optical Engineering, Bellingham, WA, 4758:7-12.

Fisher, S., N.S. Nicholas, and P.R. Scheuerman. 2002. Dendro-chemical analysis of lead and calcium in southern Appalachian American Beech. J. Environ. Qual., 31(4):1137-1145.

5.0 Acknowledgements

The Army Environmental Center (AEC) provided funding for this project. We thank Mr. Tom Vorac, Natural Resources Branch, AEC, for his interest, guidance and support throughout the project.