FINAL REPORT

APPLICABILITY OF RADAR SUBSURFACE PROFILING IN ESTIMATING SIDEWALK UNDERMINING

by

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Materials Research Analyst
and
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Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

Charlottesville, Virginia

April 1979
VHTRC 79-R44

2622

SOILS, GEOLOGY AND PAVEMENT RESEARCH ADVISORY COMMITTEE

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ABSTRACT

An evaluation was made of the applicability of the geophysical technique of radar subsurface profiling to estimating the extent of sidewalk undermining. It was found that there is a distinct difference between the observed radar echo patterns of a nonundermined sidewalk and those from an undermined sidewalk. Therefore, it is feasible to determine from the radar scan of a sidewalk the length of the sidewalk that is undermined. It is also feasible to determine the approximate depth of voids underneath an undermined sidewalk; however, this may sometimes be difficult to achieve.

The approximate cost of surveying a sidewalk with the technique was also estimated.

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INTRODUCTION

Severe undermining of sidewalks due to the erodibility of certain soils found there is a widespread problem in Fairfax County.[1] As illustrated in Figures 1 and 2, undermining removes the support from under the sidewalks and results in faulting of the joints to create hazards for pedestrians and peripheral problems in drainage and siltation. The maintenance costs associated with the undermining problem amount to several million dollars per year. Additionally, Fairfax Residency personnel believe that up to $50 million would be needed at the present time to correct the sidewalk problems throughout the county.[2]

Most of the major sidewalk maintenance is contracted so that it is desirable to have reliable estimates of materials and work quantities required before the contract is drawn. However, the nature of sidewalk undermining is such that only in the most extreme cases is it possible to accurately estimate repair quantities prior to beginning work. The result is that quantities typically run over the limit provided for in the contract. Then, in order to complete the necessary work in a given area, a new contract must be let at additional administrative costs and often at less favorable prices than in the original contract.

Clearly, a reliable method of estimating the work quantity required in the repair of an undermined sidewalk would be of great benefit to the field engineers charged with the responsibility for maintaining sidewalks.

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Figure 1. Severe sidewalk undermining.

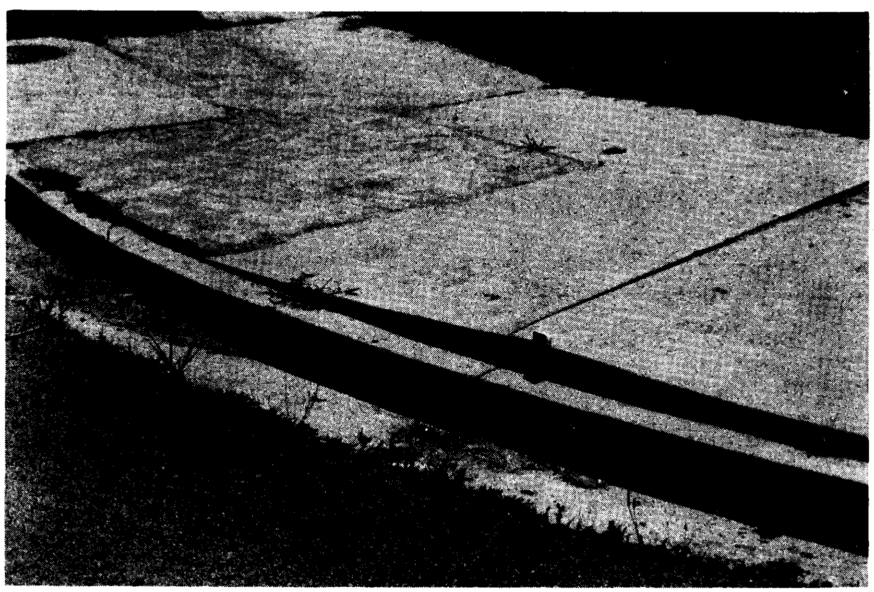


Figure 2. Sidewalk distortion due to undermining.

In recognition of this problem, the investigators made a quick survey of the geophysical techniques available, and found that the newly developed technique of short-pulse radar subsurface profiling could most likely be used to obtain a solution. Therefore, a study was undertaken to assess the applicability of the technique in estimating the extent of voids underneath concrete sidewalks.

PRINCIPLE OF RADAR SUBSURFACE PROFILING

In the radar subsurface profiling technique, a transducer unit transmits a radar pulse of fixed pulse width and at some constant time interval into the earth or other media to be tested. When the pulse strikes an interface between two subsurface materials of differing electrical properties, some of the pulse energy is reflected and the remainder continues on through the interface into the second material until it strikes another interface, and so on. The reflected pulse energy, E_r, from a given interface is related to the incident energy, E_o, by the relationship[3]

$$\rho_{12} = \frac{E_r}{E_o} = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2}, \tag{1}$$

where

ρ_{12} = the reflection coefficient at the interface between materials 1 and 2; and

ε_1, ε_2 = the relative dielectric constants for materials 1 and 2, respectively.

(If material 2 has a relative dielectric constant greater than that of material 1, then the reflection coefficient has a negative value. Thus, the reflected pulse will have polarity opposite to the transmitted pulse.) The reflected pulses, or echoes, are then received by the transducer where replicas of the transmitted pulse, followed by the reflected pulses, are generated and sent to a control unit to be monitored on an oscilloscope and printed on a facsimile graphic recorder.

After it is determined which radar echo corresponds to the reflection from which interface, the thickness (D_m) of a given layer of subsurface material (m) through which the pulses have passed can be estimated from the relationship[4]

$$D_m = \frac{t_m V_m}{2}, \qquad (2)$$

where

t_m = elapsed time between the reflected pulses from the top and the bottom of the material; and

V_m = radar pulse propagation velocity through the material for normal incidence.

V_m is related to the relative dielectric constant of the material, ε_m, by

$$V_m = \frac{C}{\varepsilon_m}, \qquad (3)$$

where

C = the radar pulse propagation velocity through air, which is 1 ft/ns.

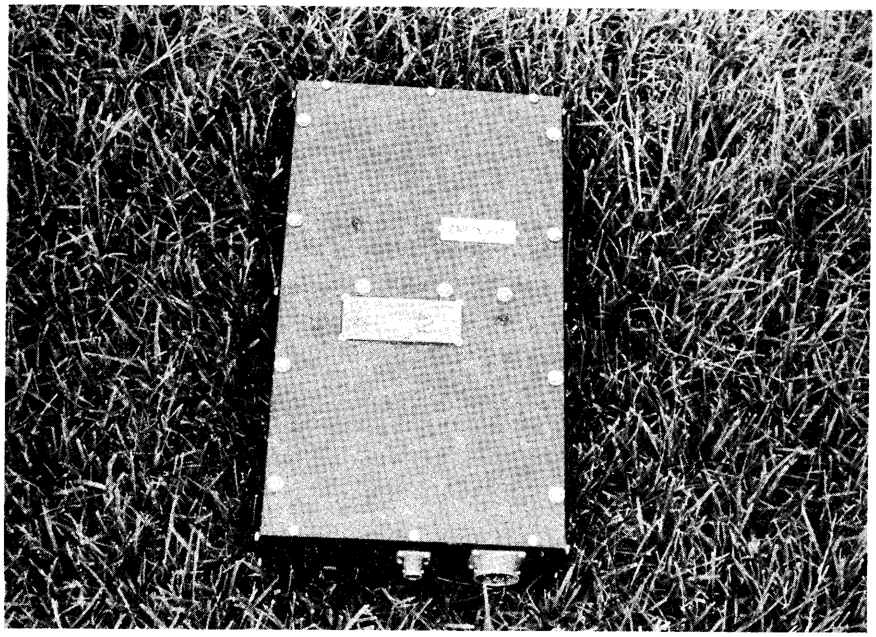
EXPERIMENTAL PROCEDURES

To determine whether radar subsurface profiling could be applied in estimating the extent of sidewalk undermining, two sidewalks with apparent undermining were selected and surveyed by the radar technique. One of the sidewalks was located along Ponderosa Drive and the other along Thames Street, both in subdivisions bordering Braddock Road in Fairfax County. The lengths of the sidewalks surveyed were from 200-300 feet (67-100 m).

Procedure Used in Radar Subsurface Profiling

Instrumentation

The radar system used was manufactured by the Geophysical Survey Systems, Incorporated, of Hudson, New Hampshire. The major components of the system (Figure 3) included a Model 4400 Radar Control Unit, a Model 101C Transducer (900 MH_z or 1.1 ns), a Model EPC 2208 Graphic Recorder, and a magnetic tape recorder. Power was supplied by a 12-volt car battery through a Model 02 Power Distribution Unit.



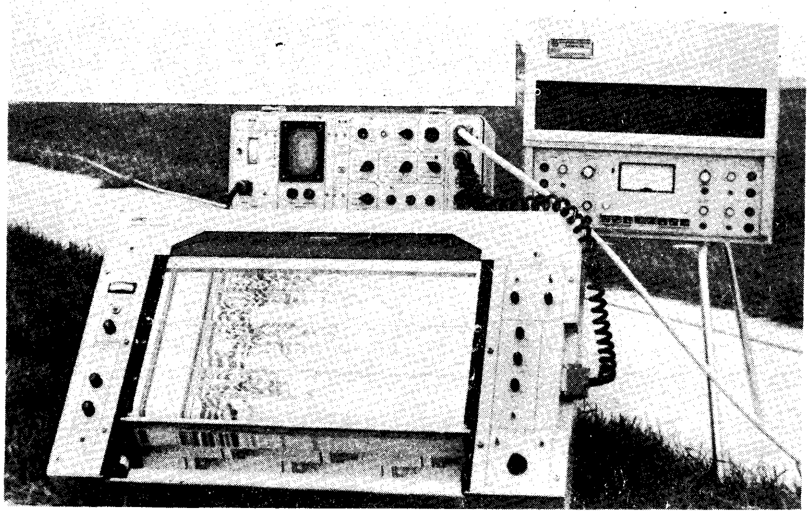


Figure 3. Instrumentation for radar subsurface profiling.

Top : Radar transducer. It measures 3 x 7 x 12 in. (8 x 18 x 31 cm); operates at a center frequency of 900 MHz and transmits a pulse signal at 20-microsecond intervals.

Bottom: Clockwise from the lower left — the graphic recorder, control unit, and magnetic tape recorder.

Prior to the survey of the sidewalks, the chart was calibrated with a 10-nanosecond calibrator so that the elapsed time for any radar echo could be estimated from the echo pattern recorded on the chart.

Survey Procedure

Four simulated sidewalk underminings of different depths (4, 11, 26, and 36 inches or 100, 280, 660, and 910 mm, respectively) were prepared by digging trenches roughly 3 ft. (0.9 m) wide and covering them with old concrete slabs previously removed from undermined sidewalks. Then, the radar transducer was placed successively over each simulated undermined sidewalk and the corresponding stationary radar echo pattern was recorded. A similar radar measurement was also made with a slab placed over solid ground with no void at all.

In surveying the two selected sidewalks with the radar system, each was marked with curb ticks at 4-ft. (1.2 m) intervals. Then the transducer was placed at approximately midwidth of the sidewalk, which is approximately 4 ft. (1.2 m) wide, and pulled by an operator along the length of the sidewalk at a pace of approximately 1 ft./s (0.3 m/s). As the transducer passed by a benchmark on the sidewalk, the operator activated a hand-held remote marker that provided an electrical signal for the graphic recorder to automatically mark the chart for locational purposes. In this manner, the chart recorder provided a linear scan (such as that shown later in Figure 11) which, as later discussion indicates, reflects variations in the extent of undermining underneath the middle portion of the sidewalk. From the recorded profiles, numerous spots of varied undermining on each sidewalk were selected for a more detailed lateral survey. This survey was performed by recording the radar echo patterns as the radar transducer was placed and left stationary first on the left third, then the middle, and finally the right third of each selected sidewalk spot.

Procedure Used in Physical Measurement of Undermining

Shortly after the two sidewalks were surveyed by radar subsurface profiling, the slabs were carefully removed to permit the actual extent of undermining to be measured. The measurement was accomplished with a photographic technique which incorporates a microtopographic profile gauge described by Allen and Curtis.(5) However, a slightly modified version of the gauge was constructed and used in this study. The device, as shown in use in Figure 4,

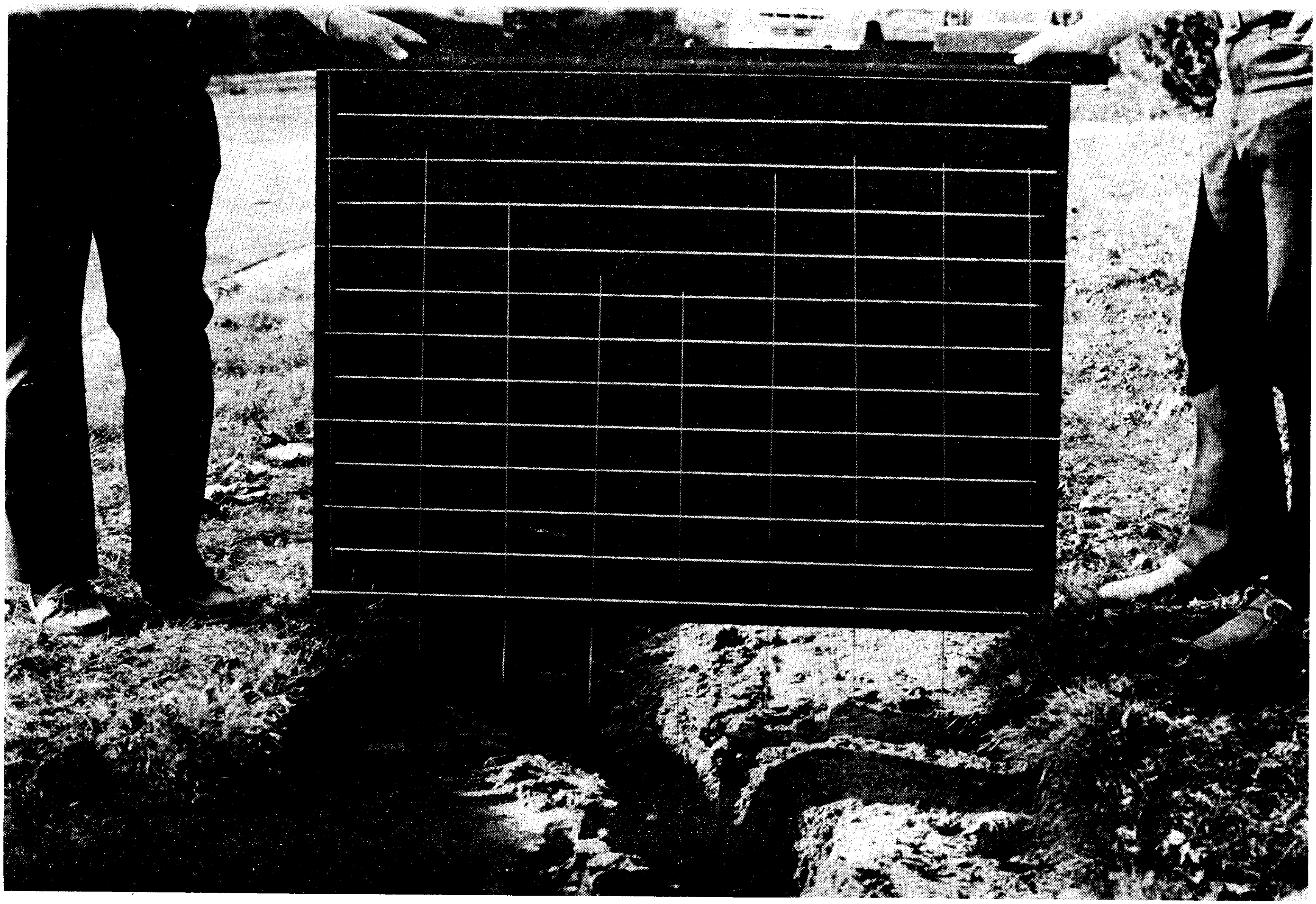


Figure 4. Physical measurement of actual undermining using a microtopographic profile gauge.

was a wooden frame measuring 3 ft. (0.9 m) high and 4 ft. (1.2 m) wide (the standard sidewalk width) that holds nine 3-ft. (0.9 m) metal pins 0.5 ft. (0.15 m) apart. The pins are arranged so they can freely move vertically before a scale formed by horizontal lines spaced 3 in. (75 mm) apart on a black backboard. When the gauge is placed over the undermined sidewalk, the pins drop and rest at the bottom of the undermining and a profile is graphed by the tops of the pins against the backboard. The undermining profile can then be photographed.

Using this photographic technique, profiles of the undermining underneath the two sidewalks were made at 4-ft. (1.2-m) intervals to provide a means by which the applicability of radar subsurface profiling could be evaluated.

RESULTS AND DISCUSSION

Correlation of Void Depth and Radar Echo Elapsed Time

The radar echo waveforms observed for the five simulated undermined sidewalks are shown in Figure 5 as they appeared on the oscilloscope of the control unit. To simplify interpretation, one can have only the negative peaks in each waveform printed on the facsimile chart recorder to obtain the echo patterns shown in Figure 6. The intensity of each band in the echo patterns corresponds directly to the amplitude of the peaks in the waveforms.

At the top of Figure 5 and the left of Figure 6 are the waveform and the echo pattern, respectively, for the composite radar echo detected by the radar transducer where there was no void between the concrete slab and the sandy soil base. The waveform and echo pattern for the zero void case are distinctly different from those for the cases which correspond to simulated undermining or voids of various extents, in that the third and succeeding bands are relatively much weaker for the zero void case.

In order to understand each echo pattern, one may start with the left pattern and consider the simplistic case of an air/concrete/soil system wherein no void exists underneath the concrete sidewalk slab, as depicted in Figure 7. When a transmitted radar pulse strikes the air/concrete interface, part of the pulse energy as determined by the reflection coefficient of this interface is reflected (R1), and the remainder penetrates into the concrete slab. This remaining pulse eventually strikes the concrete/soil interface and, similarly, part of it, depending on the reflection coefficient at this interface, will be reflected. The reflected pulse will traverse back through the concrete until it strikes the

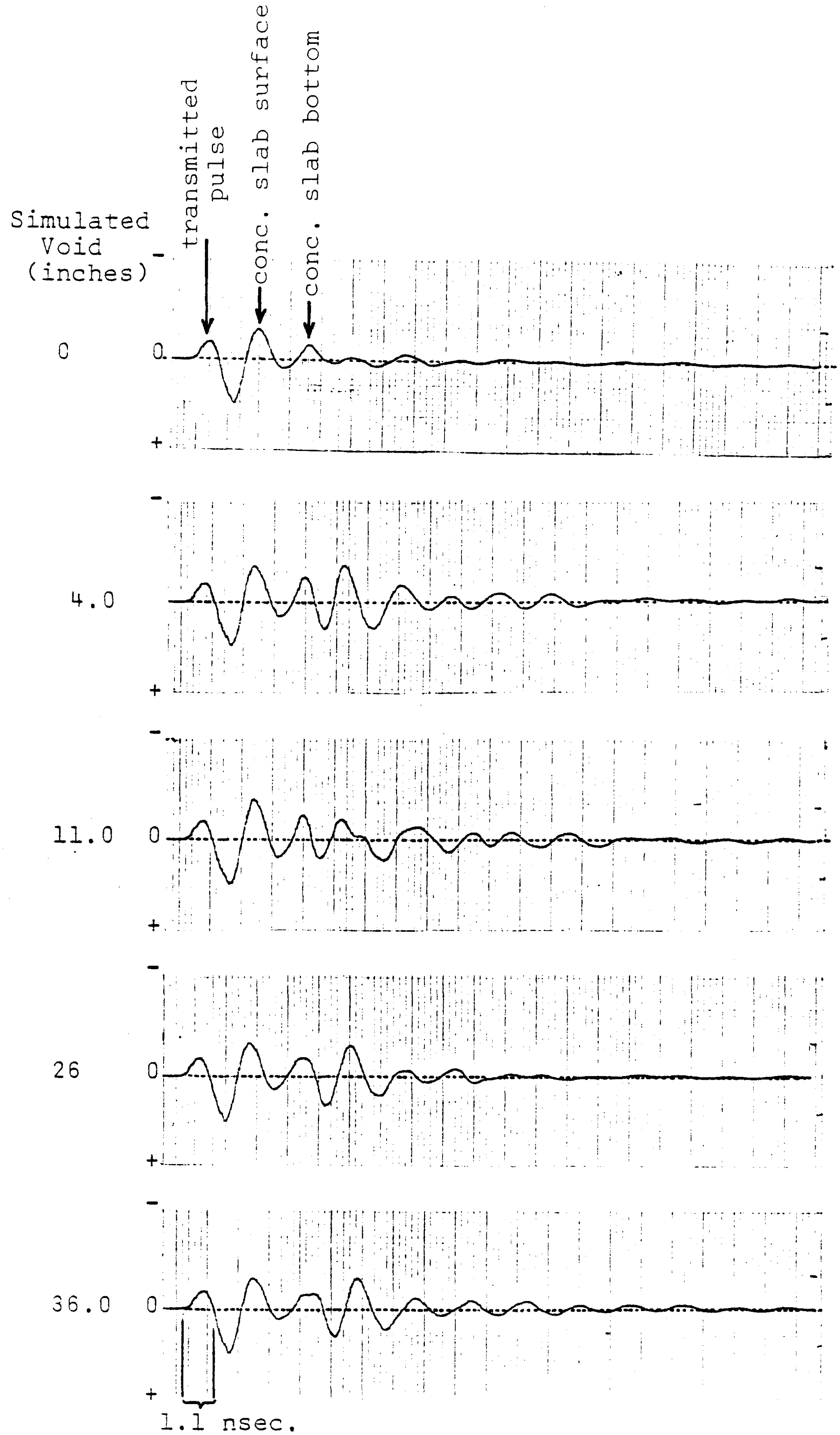


Figure 5. Radar echo waveforms observed for the simulated sidewalks of different void sizes underneath the concrete slab. Metric conversion: 1 inch = 25.4 mm.

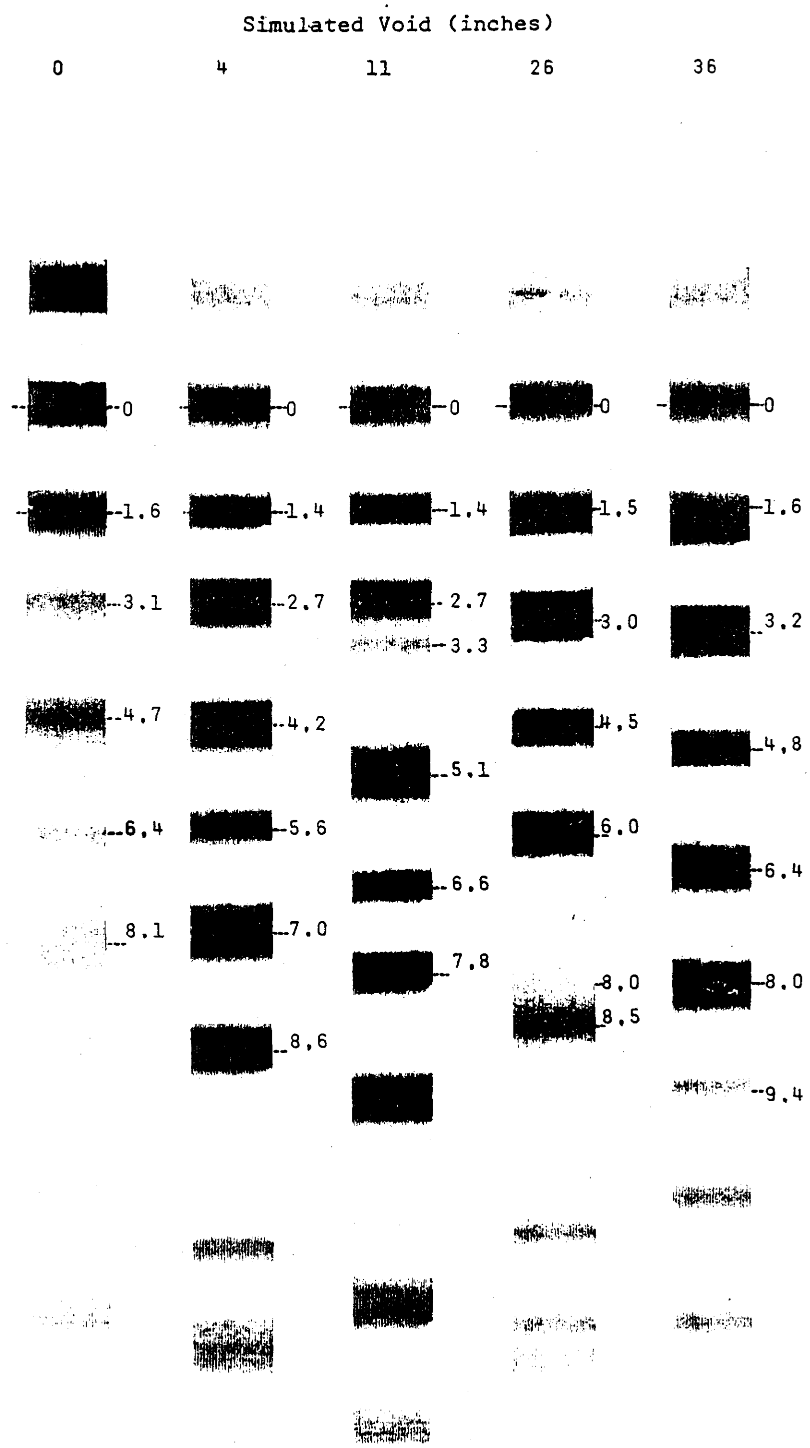


Figure 6. Radar echo patterns observed for the different simulated sidewalk underminings. The measured elapsed times in nonoseconds are noted beside each band. Metric conversion: 1 inch = 25.4 mm.

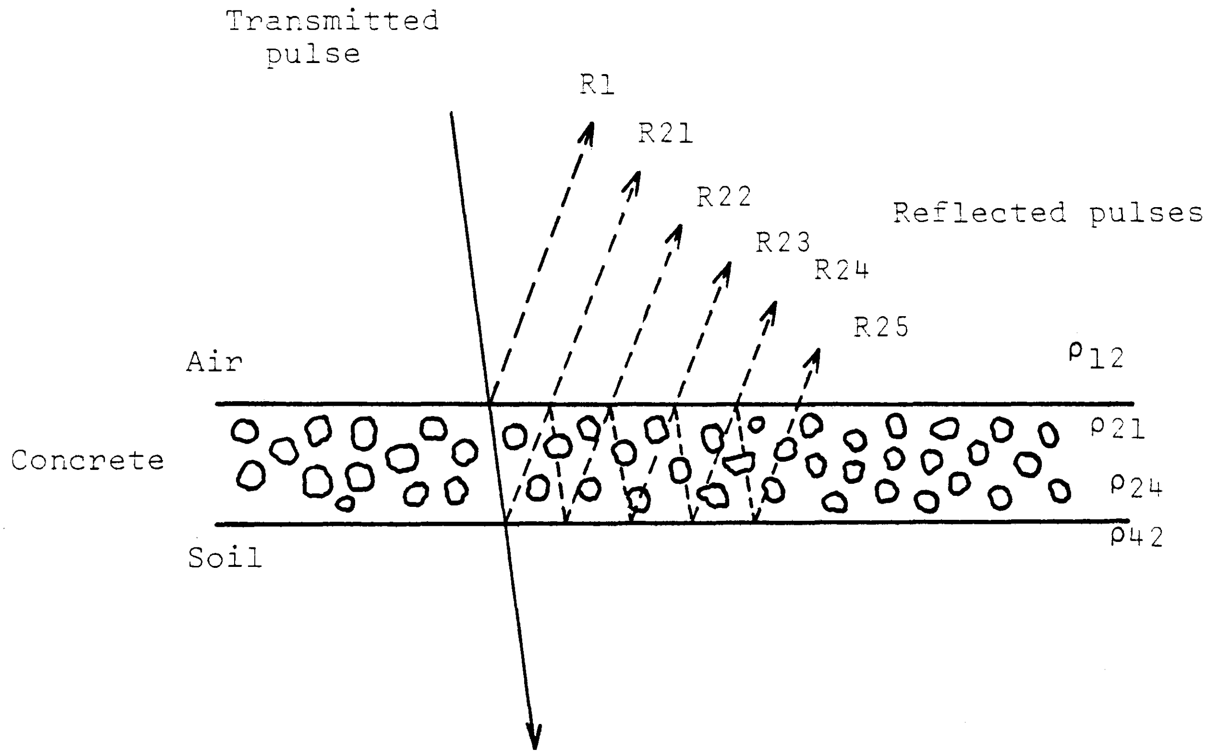


Figure 7. Propagation of radar pulses in an air/concrete/soil system.

concrete/air interface, where part of it (R21) will penetrate through and reach the radar transducer while the remainder may reverberate within the concrete slab. After one, two, three, four, or more reverberations, this remaining pulse eventually penetrates the concrete/air interface as pulses R22, R23, R24, and so on. For purposes of analysis, only a finite number of reflections need to be considered since each succeeding reflected pulse is weaker than the preceding one, as is evident in Figures 5 and 6.

Therefore, the radar echo pattern on the left of Figure 6 for the simulated sidewalk with no undermining is made up of contributions from reflected pulses R1, R21, R22, ... and R25 at least, which are depicted in Figure 7. To confirm this, the relative energy and elapsed time of each echo were derived by applying equations 1-3 and obtaining the approximate mathematical expressions in Table 1. Then, using dielectric constants (Table 2) found in the literature the energy and time parameters were estimated and are given in Table 3 along with the observed elapsed times for comparison. The excellent agreement between the estimated and observed elapsed time is obvious. The agreement between the estimated relative energy and the intensity of the corresponding band on the left echo pattern is less obvious because of the misleading periodic fluctuation in the intensities of echoes R21, R22, etc. However, this fluctuation is explained by the alternate changes in the polarity and resultant canceling effect of the estimated energy of the echoes as shown in Table 3.

Table 1

Approximate Mathematical Descriptions of the Reflected Pulses from an Air/Concrete/Soil System

Reflected Pulse	Relative Energy	Elapsed Time, ns
R1	ρ_{12}	0
R21	$(1-\rho_{12}^2)\ \rho_{24}$	$t_c = \dfrac{D_c\ (in)}{2.45}$
R22	$(1-\rho_{12}^2)\ \rho_{21}\ \rho_{24}^2$	$2t_c$
R23	$(1-\rho_{12}^2)\ \rho_{21}^2\rho_{24}^3$	$3t_c$
R24	$(1-\rho_{12}^2)\ \rho_{21}^3\rho_{24}^4$	$4t_c$
R25	$(1-\rho_{12}^2)\ \rho_{21}^4\rho_{24}^5$	$5t_c$

t_c = the propagation time for a pulse to traverse through the concrete and back.

Table 2

Approximate Dielectric Constants of Some Materials

Material	Approximate Dielectric Constant	Reference Source
Air	1	4
Sand (Saturated with Moisture)	30	4
Silt (Saturated with Moisture)	10	4
Concrete	6	3

Table 3

Estimated Energy and Time Lapse in Comparison with Observed Time Lapses for Air/Concrete/Soil System

Reflected Pulse	Estimated		Observed
	Rel. Energy	Elapsed Time, ns	Elapsed Time, ns
R1	-4.2×10^{-1}	0	0
R21	-3.1×10^{-2}	1.6*	1.6
R22	$+5.1 \times 10^{-2}$	3.2	3.1
R23	-8.1×10^{-3}	4.8	4.7
R24	$+1.3 \times 10^{-3}$	6.4	6.4
R25	-2.0×10^{-4}	8.0	8.1

*Estimated based on the standard thickness of concrete sidewalk, 4 in (10 cm).

The echo patterns observed for the different simulated sidewalk underminings can, similarly, be understood by comparing the air/concrete/air/soil system depicted in Figure 8 with the air/concrete/soil system in Figure 7. With the presence of not only more but also different interfaces from which a transmitted pulse can be reflected, the air/concrete/air/soil system would yield more reflected pulses. This is evident in the echo patterns observed for the simulated sidewalks with various degrees of undermining, which have more bands than the pattern for a simulated sidewalk with no undermining (Figure 6). The former patterns are more intense too, because, in general, the concrete/air and air/soil interfaces have higher reflection coefficients than the concrete/soil interface in an air/concrete/soil system, which is equivalent to a sidewalk with no undermining.

The above explains why the radar echo pattern for a sidewalk with no undermining is distinctly different from echo patterns for undermined sidewalks and, therefore, why, qualitatively, one can identify or locate undermined areas under sidewalks nondestructively.

The various reflected pulses depicted in Figure 8 give rise to the composite echo patterns shown in Figure 6 for the different extents of simulated undermining. Depending on their polarity and elapsed time, some of these reflected pulses will have either a canceling or an enhancing effect on each other, since the radar pulses used in this study have a pulse length of about 1.1 nanosecond. For quantitative determinations of void depths underneath concrete sidewalks the elapsed time corresponding to reflected pulses 31, 32, or 41 (in the order of decreasing importance) could be used in the generalized relationship

$$D_v = \frac{6\ (t - 0.41\ N_c D_c)}{N_v}, \tag{4}$$

where

D_v = void depth, in in;

D_c = concrete slab thickness, in in;

t = elapsed time between reflected pulses 1 and 31, 32, or 41, in nanoseconds; and

N_v, N_c = number of round trips the above pulses made through the void or concrete, respectively,

which is derived from equations 1-3. However, before this approach can be used, one of the reflected pulses in any given

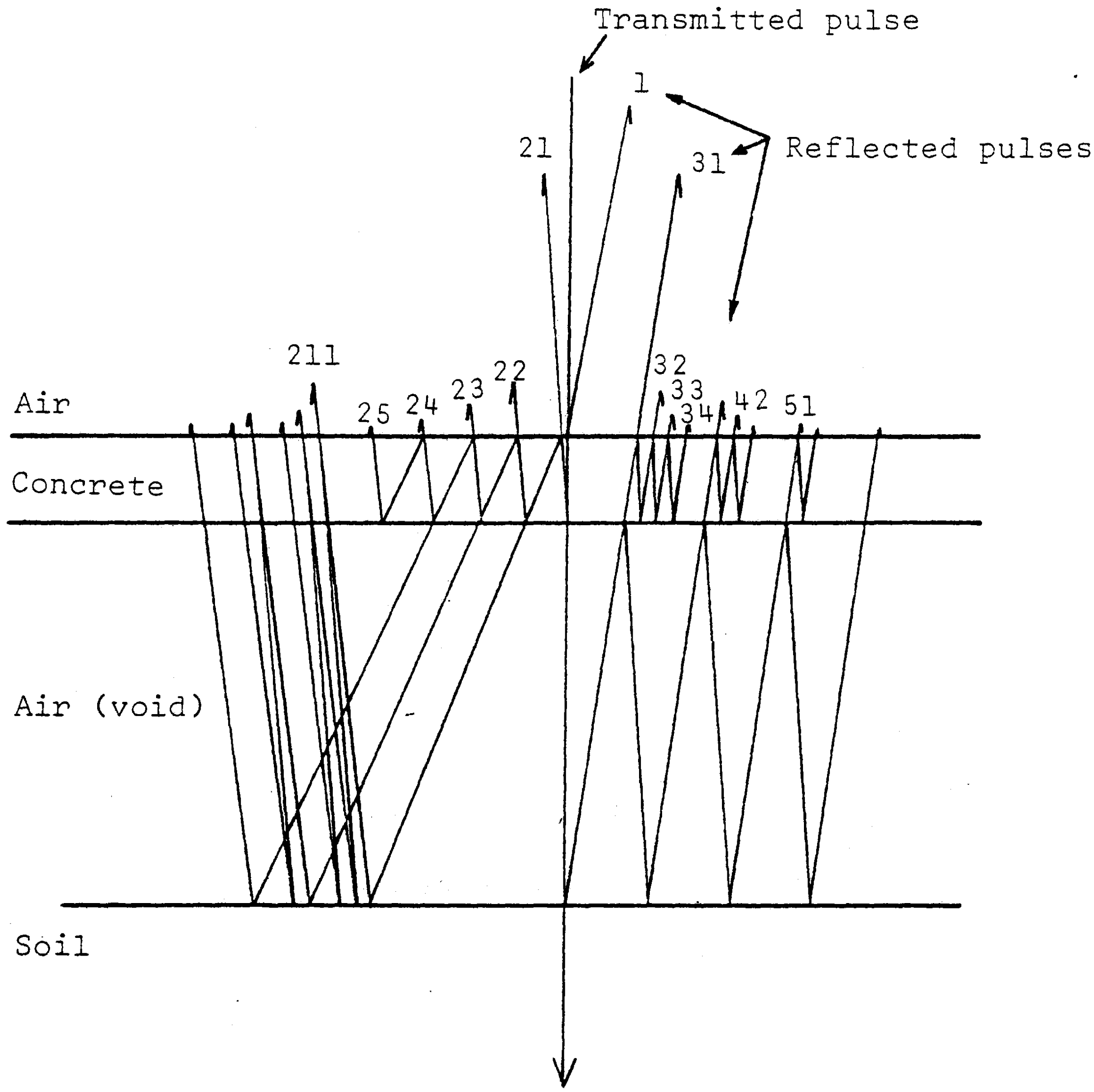


Figure 8. Propagation of radar pulses in an air/concrete/air/soil system.

composite echo pattern of an unknown void depth has to be identified. It is obvious, from an examination of Figure 6, that developing a simple way for the identification of these pulses is at least an extremely difficult if not an impossible task. Therefore, this relatively straightforward approach will likely be used only seldomly and an alternative must be developed.

For the purpose of verifying some of the stationary radar echo patterns observed in the two undermined sidewalks, in addition to those in Figure 6 for the simulated undermined sidewalks, the authors developed an alternative approach which can be described as "echo pattern matching." In this approach, the elapsed times corresponding to an assumed void depth are estimated for the major reflected pulses depicted in Figure 8 by using equation 4. This estimating generates a theoretical or expected echo pattern consisting of expected elapsed times for the assumed void depth. When repeated over a range of assumed void depths, at practical intervals, the estimates produce a set of theoretical echo patterns with which any given unknown echo pattern could be compared or matched. The corresponding void depth of the theoretical echo pattern that best matches the unknown echo pattern would, therefore, be the most probable unknown or sought-for void depth.

Using this approach, the radar echo patterns for the four simulated void depths in Figure 6 were compared with theoretical echo patterns as shown in Table 4. Except for the fact that some of the calculated reflected pulses for the two shallow voids were not observed, the agreement is extremely good. A more exact calculation of the theoretical patterns, including the polarities and relative magnitudes of the reflected pulses, would show how those pulses separated by less than one full pulse width of 1.1 nanoseconds overlapped and canceled each other, thereby accounting for the absences of some close reflected pulses of opposite polarities in the observed echo patterns.

The good agreement between the observed and theoretical echo patterns for the simulated sidewalk underminings indicates that the radar subsurface probing technique can be used to reliably determine void depths in these ideal cases. To test the reliability of the technique under the less ideal situation of a real undermined sidewalk, whose void geometry can often be more complicated than the wide trenches used to simulate undermined sidewalks, stationary echo patterns at several selected spots along the two study sidewalks were recorded. Then, each echo pattern was matched against a set of theoretical or expected patterns corresponding to a range of void depths at 1-in intervals. Figure 9 shows some examples of results obtained when radar-determined void depths were compared against the measured actual voids or underminings. As illustrated, the radar-determined depths have an uncertainty of at least 1 in., because it was often difficult to exactly match an unknown pattern against a single theoretical pattern. The overall agreement in these examples could be described as fairly good. However, it must be emphasized that there were some unknown radar echo patterns, belonging to different sidewalk spots of almost identical actual void depths, that are therefore expected to match each other but did not match well. Such discrepancies could have been caused partly by the complicated geometry that characterized some of the undermining. It is suspected that a gully with an extremely small width-to-depth ratio would probably have a significantly different echo pattern than a gully of identical depth but a larger width-to-depth ratio, since the radar pulses are transmitted in a 90° conical shape. Variations in the moisture content and the occasional presence of rocks in the soil base would also affect the radar echo pattern.

In the preceding discussion it has been shown that the void depth at any spot in an undermined sidewalk could be determined from the stationary radar echo pattern observed for that spot. In an actual application, however, it may not be necessary to determine the exact void depth; rather, it may be sufficient to determine the length of a sidewalk that is undermined. In such a case, the sidewalk can be scanned with the radar system by pulling the radar transducer over and along the length of the sidewalk while the facsimile chart recorder provides a continuous record of the varying echo pattern, which reflects how the void depth varies. As shall be illustrated in the next section, one can deduce from such a linear sidewalk scan the extent of undermining in a length of sidewalk.

Table 4

Comparison of the Theoretical and Observed Echo Patterns
for the Simulated Sidewalk Underminings

Simulated Void Depth (in.)											
4			11			26			36		
Pulse	Elap. Time, ns		Pulse	Elap. Time, ns		Pulse	Elap. Time, ns		Pulse	Elap. Time, ns	
	Calc.	Obs.		Calc.	Obs.		Calc.	Obs.		Calc.	Obs.
1	0	0	1	0	0	1	0	0	1	0	0
21	1.4	1.4	21	1.4	1.4	21	1.5	1.5	21	1.6	1.6
31	2.1		22	2.9	2.7	22	3.0	3.0	22	3.2	3.2
41	2.8	2.7	31	3.3	3.3	23	4.5	4.5	23	4.7	4.8
22	2.9		23	4.3		31	5.8		24	6.3	6.4
51	3.4		32	4.7	5.1	24	6.0	6.0	31	7.6	8.0
32	3.5		41	5.1		32	7.3		25	7.9	
61	4.1		24	5.7		25	7.5	8.0	32	9.1	9.4
42	4.2	4.2	33	6.1		33	8.8	8.5	33	10.7	10.9
23	4.3		42	6.5	6.6						
52	4.9		51	6.9							
33	5.0		25	7.2							
43	5.6	5.6	34	7.6							
24	5.7		43	8.0	7.8						
34	6.4										
25	7.1	7.0									
26	8.6	8.6									

Metric conversion: 1 inch = 25.4 mm.

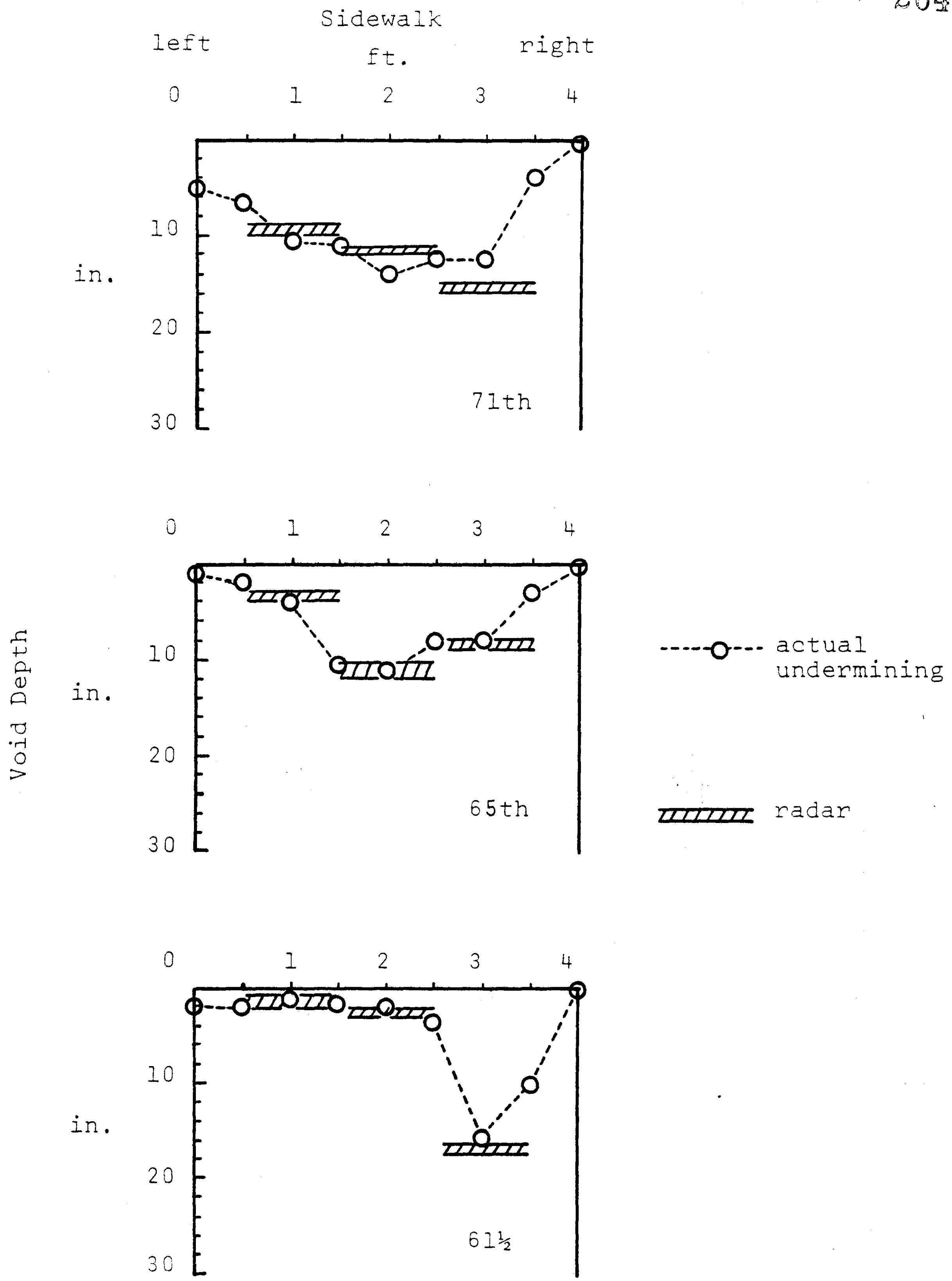


Figure 9. Comparison of some radar results with actual undermining profile. Metric conversion: 1 inch = 25.4 mm.

Linear Scan of Sidewalk Undermining

When the radar transducer was placed over a piece of old concrete sidewalk seated on solid ground, it was possible, simply by gradually raising the concrete slab from the ground, to simulate scanning of a sidewalk which has a gradual increase in void depth along its length. The recorded pattern simulated a linear scan of such a simulated sidewalk. A scan obtained from such a simulation, to a maximum void depth of approximately 12 in. (30 cm), is shown in Figure 10. This figure vividly illustrates that, as expected from conclusions drawn in the earlier discussion, the echo pattern corresponding to the presence of any void underneath a sidewalk is distinctly characterized by more reflected pulses of very high amplitudes in comparison to that of a solid or non-undermined sidewalk.

In Figure 11, the linear scan of one of the two selected sidewalks is shown superimposed over a graph representing the actual undermining that had occurred underneath the middle portion of the sidewalk. As previously discussed, the radar echo pattern for solid sidewalk is characterized by few and weak reflected pulses. Based on this, one could say that from the radar scan there were two stretches of relatively less undermined sidewalk (between benchmarks 7 to 14 and 45 to 54) with four shorter stretche between them. It is obvious that the agreement with the physically measured undermining is extremely good.

PROPOSED APPLICATION AND COST ESTIMATE

From the foregoing discussion it is fairly evident that the radar subsurface profiling technique could meet the need for improved accuracy in estimating the extent of undermining needing repair. With the technique, it would be desirable to evaluate sidewalks for their full lengths in an area where repairs are anticipated. Such an evaluation should include two scans of each sidewalk at approximately the one-third width points for good coverage.

The estimated cost of such surveys, based on estimated work rates and salaries and equipment costs provided by the manufacturer, would be $50 per mile of sidewalk. In developing the estimate it is assumed that one full-time man will be required for the estimated 10-year service life of the equipment. The values used in developing the estimate are listed in Table 5.

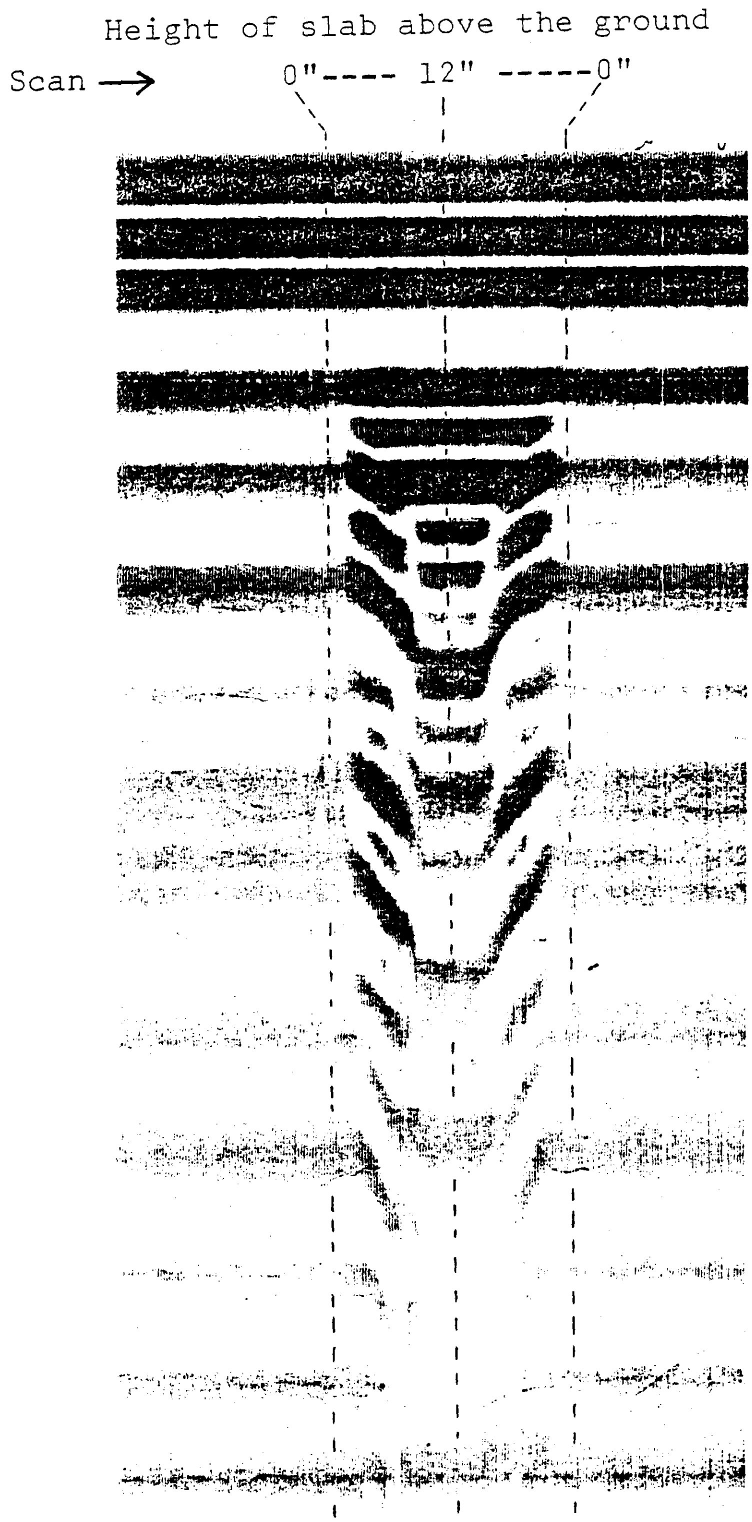


Figure 10. A simulated linear radar scan of a segment of sidewalk. (A concrete slab was gradually raised from the ground and returned.) Metric conversion: 1 inch = 25.4 mm.

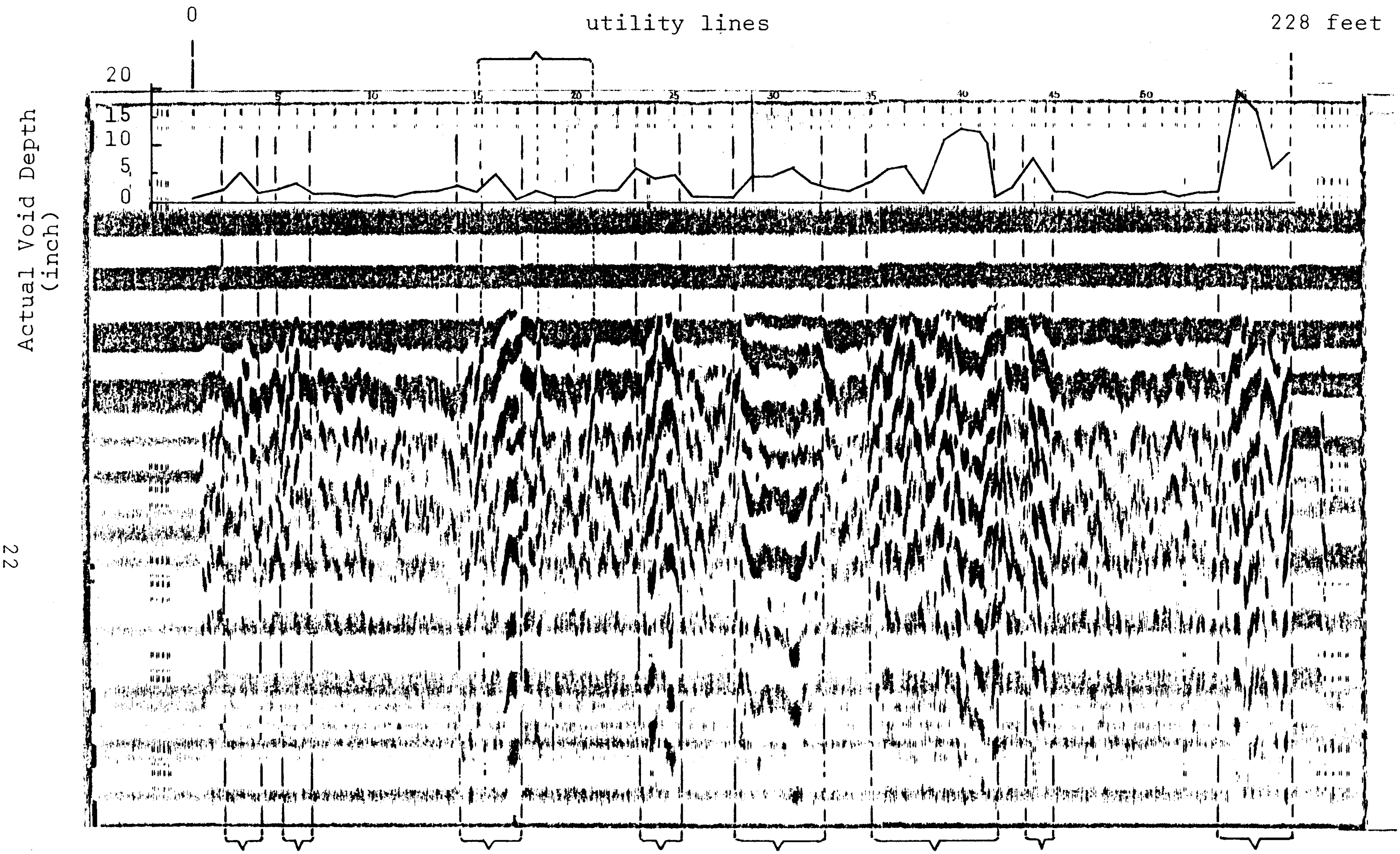


Figure 11. Linear radar scan of a 228-ft. segment of sidewalk along Ponderosa Drive in Fairfax County. The graph above it shows the undermining physically measured after the concrete slabs were removed.

Table 5

Values Used in Cost Estimate

Labor		
Salary and overhead	—	$10.00 per hour
Survey Rate	—	2 mile per day
Equipment		
Radar	—	$23,000
Supplies	—	$ 1,000
Maintenance	—	$ 2,000

Although no studies of such have been incorporated in the present study, it has been established that the radar technique evaluated is capable of evaluating voids under pavements and could be useful in the development of undersealing and drainage repair contracts.(3)

SUMMARY OF CONCLUSIONS

The conclusions made in previous sections can be summarized as follows:

1. The characteristic radar echo pattern for an air/concrete/soil system, or a nonundermined concrete sidewalk, is distinctly different from that of an air/concrete/void/soil system, or an undermined sidewalk. This is because, in general, more reflected radar pulses with high energies are observed with increased void depth.

2. It is feasible to determine from a radar scan the extent of undermining that has occurred in a length of sidewalk.

3. If necessary, it is possible to determine the depth of voids underneath an undermined sidewalk through "echo pattern matching." However, due to complications in the echo pattern caused by some factors, this may sometimes be difficult to achieve.

RECOMMENDATION

Based on the information presented in this report it is recommended that the Department consider the purchase and use of radar equipment similar to that evaluated. The primary use of the equipment could be for detecting sidewalk undermining, but it could be useful in the assessment of subsurface pavement voids. The manufacturer of the equipment evaluated provides a training period at its plant as a part of the purchase price. Given this training, an individual meeting the qualifications for the highway technician salary series would be capable of conducting the survey and interpreting the data.

ACKNOWLEDGMENTS

The authors thank Assistant Resident Engineer P. D. Gribok and Inspector J.Phillips of the Fairfax Residency for their help in the many arrangements required for the successful completion of the field work for the study. Also, appreciation is expressed for the assistance rendered by Messrs. R. W. Gunn and J. W. French of the Research Council staff.

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