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FINAL REPORT

USE OF GROUND-PENETRATING RADAR FOR DETECTING VOIDS UNDERNEATH A JOINTED CONCRETE PAVEMENT

by

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

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ABSTRACT

A survey of a jointed, reinforced concrete pavement with ground-penetrating radar indicated that the equipment provides a nondestructive inspection technique that can be used at a minimum rate of 5 lane miles of pavement per hour and with only minimal interference with traffic. The coring of some slabs and subsequent use of a devised water test revealed that the radar was very effective in detecting voids deeper than 1/8 in but considerably less effective in spotting shallow voids. The overall accuracy was approximately 68%, which indicates that the sensitivity of the equipment needs to be improved. The location component used with the radar unit showed insufficient accuracy.

A regression analysis of the recorded quantities of grout used daily in subsealing portions of the pavement versus the total linear feet of voids detected underneath the slabs grouted each day yielded only a 51% correlation. However, the regression was found to be significant at a 95% probability level. It is believed that if the width and depth of each void can be conveniently estimated so that the extent of voids can be expressed in terms of volume instead of length only, an even more successful method of estimating grout quantities would be available.

It has been shown that information derived from a radar survey can be very useful in developing a sound and cost-effective slab stabilization operation through the proper placement of grout holes.

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CONVERSION FACTORS

To Convert From	To	Multiply By
in	cm	2.54
in	m	0.0254
ft	m	0.3048
mi	km	1.6093 44
ft^3	m^3	2.8316 85 E-02
ns	s	1.0000 00 E-09
GHz	Hz	1.0000 00 E+09

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INTRODUCTION

Each year an increasing number of miles of concrete pavement in Virginia and other parts of this nation become in need of maintenance and repair. Since the formation of voids beneath the concrete slabs is a major cause of pavement failures, there is an urgent need for a rapid, nondestructive inspection technique for detecting such voids before failures occur. The value of knowing the location and extent of the voids when planning for slab stabilization is immeasurable.

Recent studies (1, 2, 3, 4) conducted at the Research Council and elsewhere have shown that cavities under concrete sidewalks, runways, and approach slabs to bridges can easily be detected with ground-penetrating radar (GPR). Consequently, there is a trend toward increasing use of this new, rapid, nondestructive technique in the inspection of concrete pavements. However, with concrete pavements, failures can occur when the gap (or void) between a slab and the subbase is only 0.125 in deep, and the ability of GPR to consistently provide accurate indications of this type of void had not been evaluated and reported prior to the research presented here.

Thus, GPR was used to survey a 14.5-mile section of Interstate Route 81 in southwestern Virginia for the purpose of (1) evaluating the accuracy of GPR in detecting voids, (2) determining if the radar could be used as a reliable method for estimating the quantities of grout needed to fill the voids, and (3) examining other possible uses of the technique.

This report describes briefly the principle of GPR and the procedure used in the survey of the I-81 pavement. It also examines the results of the survey from the standpoint of a user of GPR.

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PRINCIPLE OF GPR

Ground-penetrating, or downward-looking, radar came into existence in the late 1960s. Since then it has been put to a variety of uses, mostly public utility operations and geophysical investigations. Probably the earliest study on the use of GPR on pavement was that reported in 1974 by Bertram, Morey, and Sandler, who studied its potential application for the evaluation of airfield pavements.(5) This was followed by the similar studies mentioned earlier.(1-4) The use of GPR for detecting concrete delaminations in bridge decks (6,7) and determining the thickness of bituminous overlays on bridge decks(8) has been reported.

The radar systems used in these studies generally have been of the short-pulse type. This type operates on the principle of inducing a single pulse from a transmitter, then abruptly ceasing transmission for a short interval (typically on the order of microseconds) during which reflected signals return to a receiver. In all recent studies, the transducers (i.e., the combined transmitter and receiver) used have had a pulse width of approximately 1 nanosecond (ns). These transducers operate at relatively high frequencies (typically 1 GHz) to provide both sufficient penetration (approximately 3 ft) and the best available resolution, which is necessary when examining pavements and bridge decks. This is in contrast to the low-frequency transducers that are more suitable for geological and similar surveys, because they yield relatively greater penetration albeit poorer resolution.

When a pulse of electromagnetic energy is directed into a concrete pavement (Figure 1), a portion of the energy, P1, is reflected back to the transducer at the air/concrete boundary, which is the first boundary between two media having highly contrasting dielectric properties (Table 1). The remaining energy propagates through the concrete until it strikes another boundary, which would be the concrete/base boundary, where another portion of energy, P2, is reflected back. The portion not reflected penetrates through the layer of base material and other subsequent layers of materials to repeat the reflection-and-penetration processes until the original energy is completely dissipated. (The maximum penetration would depend upon the moisture content of the materials below the concrete slab.)

As illustrated in Figure 1, when a void exists below the concrete slab, an additional reflection, P3, is caused by the additional boundary, which is air/base (void/base). In addition, the P2 reflection would become stronger (i.e., have a larger amplitude) than that where no void exists, due to a change in the nature of the boundary (i.e., from concrete/base to concrete/air or void), with a corresponding increase in the reflectivity at the boundary. These recognizable changes in the reflection pattern of a pavement, as shown later in Figure 2, enable the detection of voids beneath the concrete slab.

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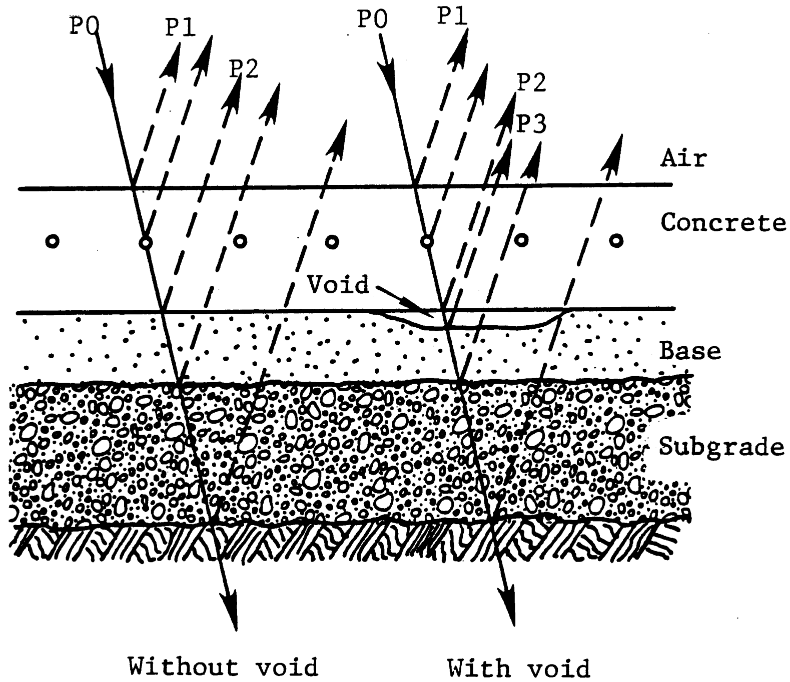

Figure 1. Propagation of microwave pulses through a concrete pavement, without and with a void underneath the concrete slab.

TABLE 1

Dielectric Constants of Materials Relevant to Pavements

Materials	Relative Dielectric Constant, ε
Air	1
Concrete	6 - 8
Sand (dry)	4 - 6
Granite (dry)	5
Limestone (dry)	7 - 9
Dolomite	6 - 8
Soil[9]	3 - 12
Water	81

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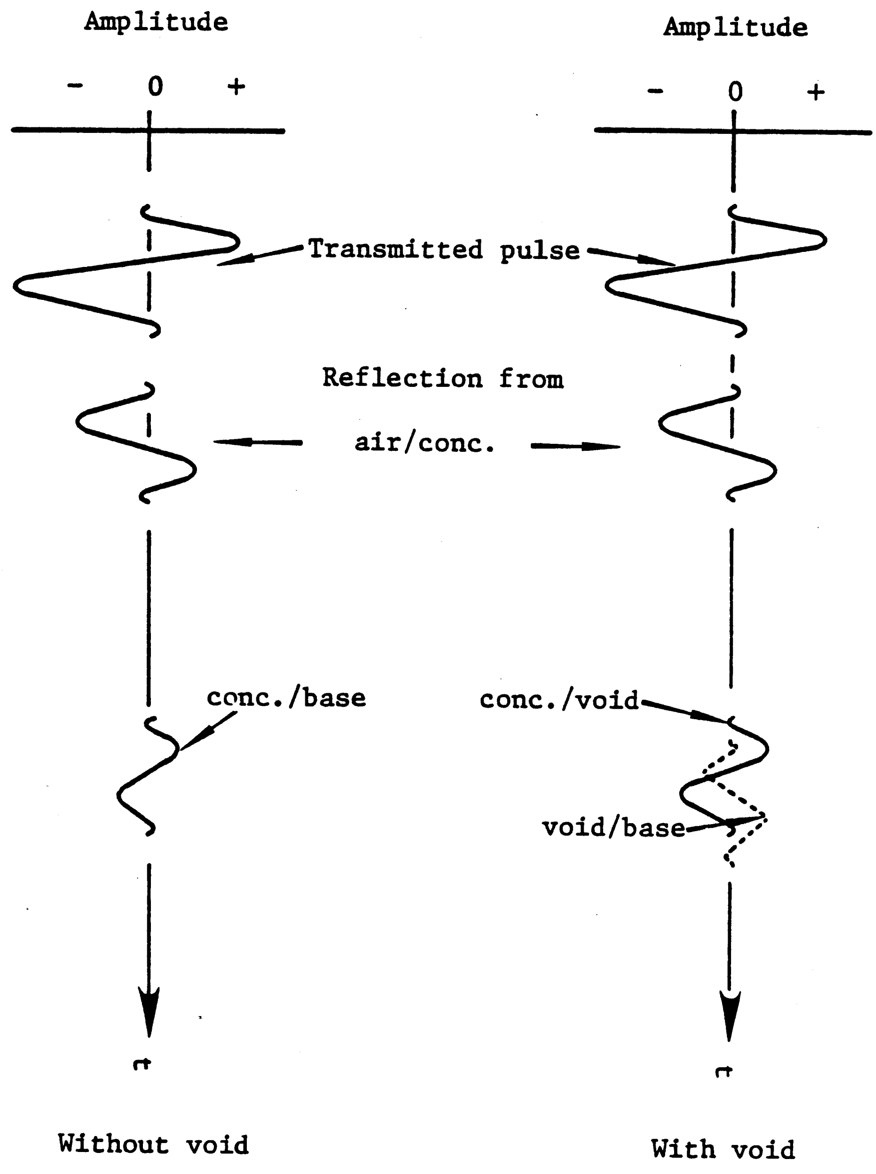

Figure 2. Microwave reflection profile for concrete pavement, without and with a void.

The amplitude (A) and polarity of the energy reflected from a boundary is governed by

$$\rho = \frac{A}{A_o} = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \quad , \qquad (1)$$

where

ρ = reflection coefficient at the boundary,

A_o = amplitude of the incident energy,

ε_1 = relative dielectric constant of medium (or material) 1, and

ε_2 = relative dielectric constant of medium (or material) 2.

In accordance with this equation, the surface of the concrete pavement (i. e., the air/concrete boundary) would have a reflectivity of negative value, because concrete has a dielectric constant greater than that of air, as indicated in Table 1. Therefore, the energy reflected from the surface of the pavement would have a negative polarity with respect to that of the transmitted pulse in Figure 2a, and an absolute amplitude proportional to A_o and $\rho_{air-conc}$.

The polarity and amplitude of the reflection P2, at the concrete/base boundary, would depend on the base material used. In the section of I-81 surveyed the base material was a 2 in sand leveling course over a 6-in layer of crushed stone (either limestone or dolomite). If the sand is dry during the survey, then P2 would likely be positive and have an amplitude only about one-tenth that of P1, as illustrated in Figure 2a. However, if the sand is moist, its dielectric constant could be considerably greater than that of concrete, so that P2 would become negative and stronger.

Where there is a void beneath the concrete slab, the concrete/base boundary is, of course, replaced by a concrete/void and then a void/sand boundary. In this case reflection P2 would remain positive, although its amplitude would become larger, maybe about one-third that of P1. In addition to this change, the additional reflection, P3, would occur and assume a negative polarity of considerable amplitude (Figure 2b).

The difference in the times at which any two successive reflections reach the receiver would depend on the thickness and the dielectric constant (ε) of the material existing between the reflection boundaries, i.e.,

$$t = \frac{2D\sqrt{\varepsilon}}{11.81} \quad , \qquad (2)$$

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where

t = pulse arrival time, or separation from a preceding reflection, in nanoseconds, and

D = thickness, in inches.

According to this relationship, reflections P1 and P2 would arrive at the receiver about 3.3 ns apart, assuming an average slab thickness of 9 in. This is considerably more than the minimum 1 ns (the pulse width that characterizes the transducer) needed to prevent their overlapping and interfering with each other.

Since the relative dielectric constant of air is 1, according to equation 2 the reflection P3 from the bottom of a void would be behind P2 in proportion of its depth; i.e.,

$$t = \frac{D}{5.9} , \qquad (3)$$

where D is the depth, in inches, of the void. It was suspected that the voids beneath the pavement slabs on I-81 would probably be no deeper than a few eighths of an inch and P3 and P2 thus would be separated by no more than 0.06 ns. This implies that P3 would often overlap P2 and, therefore, affect its amplitude, as is illustrated in Figure 2b. Again, it is by observing these changes in the reflection corresponding to the bottom of the concrete slab that voids can be detected.

During a survey the electromagnetic pulse is repeatedly transmitted through the pavement (at a rate of 50kHz for one radar system) while the radar system travels slowly (5-10 mph) over the pavement. This creates a stream of radar reflection profiles containing information on the pavement being surveyed.

RADAR SYSTEM FOR SURVEY OF PAVEMENTS

In contrast to surveys of bridge decks, which seldom cover more than several thousand feet, pavement surveys usually cover linear miles. Consequently, a radar system that is to be used to survey pavements requires a location reference unit in addition to the radar unit. Usually based on a fifth-wheel device, the location reference unit determines the precise location of the radar system on the pavement at any moment during a survey by measuring the travelled distance from a starting point.

The Virginia Department of Highways and Transportation owns a radar unit that is intended for use in surveying bridge decks and is, therefore, not integrated to a location reference unit. Consequently, the radar survey of I-81 was contracted to Gulf Applied Radar of Marietta, Georgia, which has assembled a relatively sophisticated road survey system. This system, as diagrammed in Figure 3, has a radar and a location reference unit integrated with a wide-angle video unit that records pavement surface conditions for possible correlation with subsurface conditions derived from radar data. Its radar unit operates two antennas simultaneously (Figure 4). This arrangement provides coverage over two survey paths, each approximately 18 in wide, in a traffic lane in a single pass, and thereby considerably reduces the survey time.

The system is also equipped with a reference marking unit that automatically sprays a paint mark on the pavement at 1,000-ft intervals during the survey. (This capability has since been improved to apply the marking at intervals as short as 10 ft.) This advantage and the dual-antenna setup were among the factors that influenced the decision to contract out the survey.

SURVEY PROCEDURE

The antennas were set up 5 ft apart, as shown in Figure 4. Then the survey vehicle was driven over each lane on a course such that antenna 1 was approximately 3 ft from the edge of the pavement shoulder or the longitudinal joint (Figure 5). The survey of the entire 14.5-mile section of this four-lane highway, which translates to 58.0 lane-miles of jointed concrete pavement, was accomplished with five runs made in approximately 12 hours (Figure 6). Only minimal traffic control was necessary, since any necessary lane closure was very brief.

During each run reference markers were applied on the pavement at 1,000-ft intervals.

RESULTS AND DISCUSSION

Microwave Reflection Profiles of Concrete Pavement

Figure 7 shows a pair of microwave reflection profiles that were recorded on magnetic tape during the survey and later transferred to a strip chart recorder. These are the reflection patterns for 1,200 ft of pavement on the northbound travel lane, with the top and bottom profiles corresponding to the 3- and 8-ft wheel paths, respectively. (The horizontal scale in each pattern corresponds to the traveled distance from a starting point, while the vertical scale corresponds to arrival time of the reflection at the antenna receiver, or to the depth of the various materials when the dielectric constants involved are known.)

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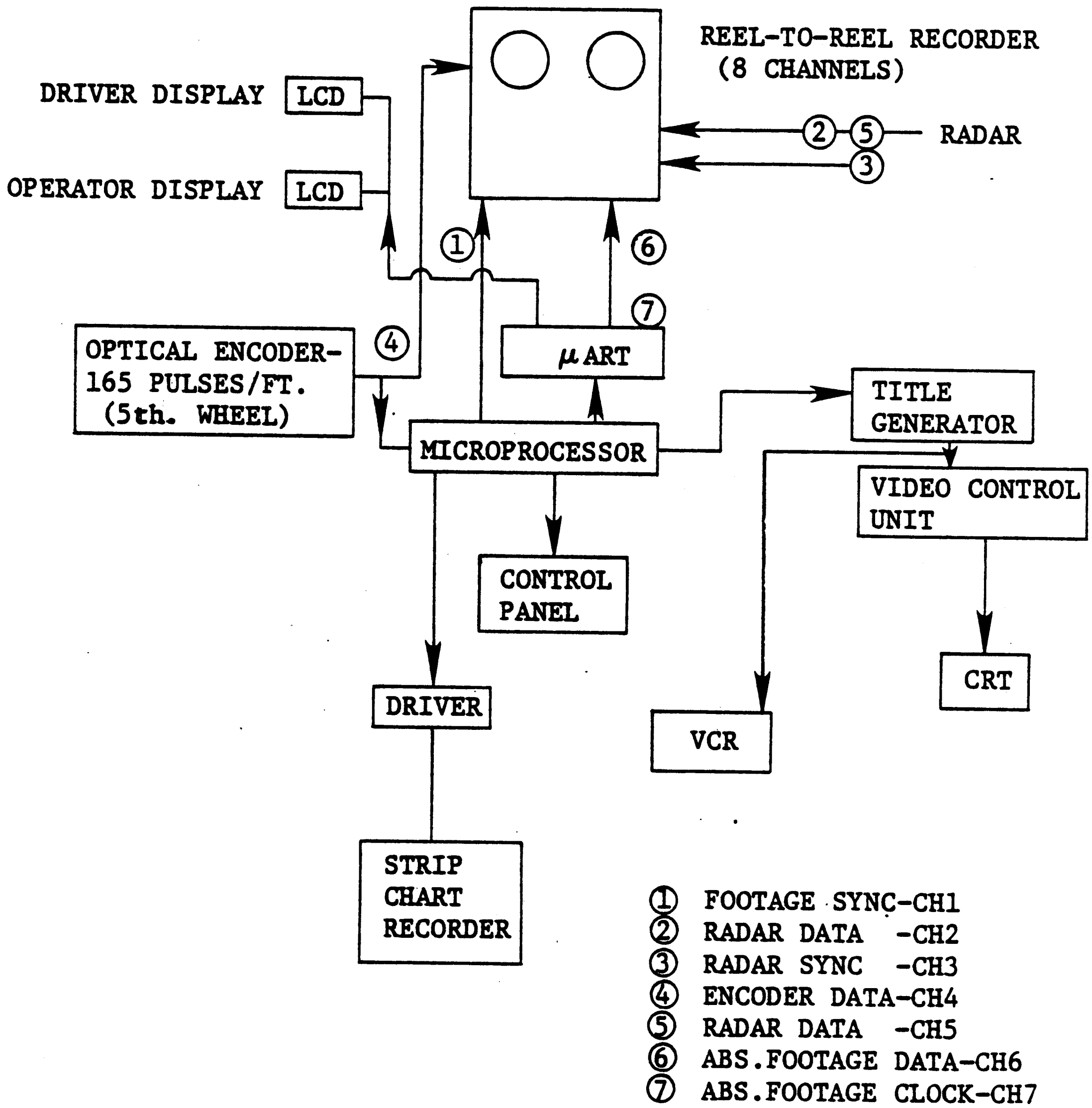

Figure 3. Diagram of Gulf Applied Radar's RODAR unit.

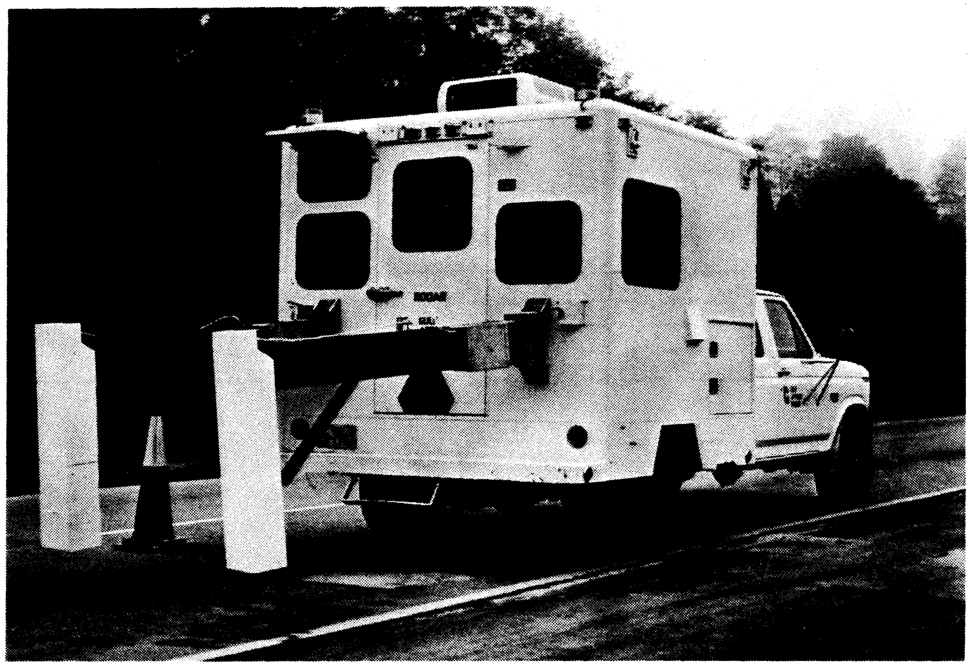

Figure 4. Photo of RODAR unit.

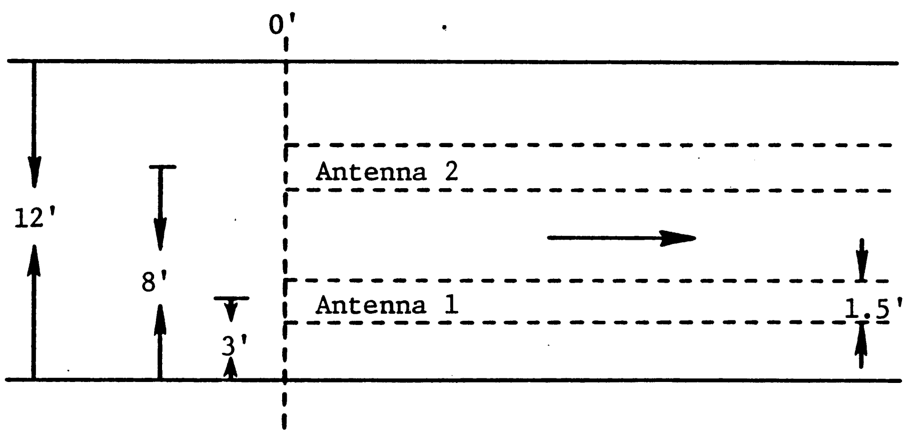

Figure 5. Antennae paths on each lane.

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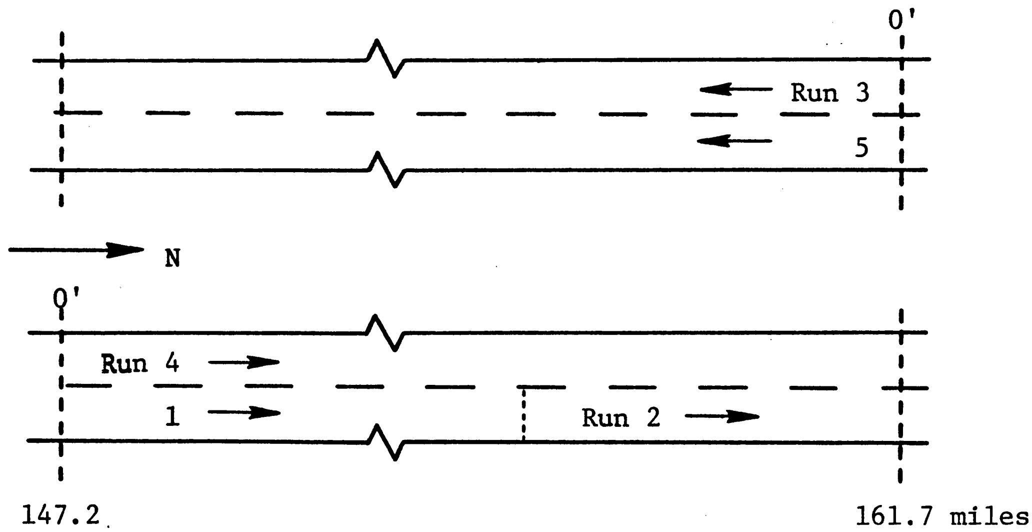

Figure 6. Radar survey runs on I-81.

For the portion of pavement shown in Figure 7, numerous voids of various sizes were evident. Each was manifested by a pair of relatively intense white-then-black bands at the concrete/base boundary caused by reflection P3 and its interaction with P2, as discussed earlier. The transverse joints, which were 61.5 ft apart, were readily recognizable as peaks at the top of a reflection profile, especially the upper one. Careful examination of this set of reflection profiles would also show that practically all of the voids were downstream of the joints, with respect to the direction of traffic flow, which is from left to right of the chart. This is particularly noteworthy of radar, since it provides a cross-sectional "picture" of what occurs underneath the concrete slab and around a joint or crack. This picture appeared to support the view of experts in pavement rehabilitation that during pumping there is a movement of particles counter to the direction of traffic across a joint (or crack) that often results in a buildup of loose materials under the slab upstream of the joint (i.e., the approach slab), while some fine materials are pumped out, through the joint or crack, from under the slab downstream of the joint (i.e., the leave slab) to create a void there.

Although not all joints showed up readily in the reflection patterns recorded, joints with severely damaged sealant were very distinct, as shown in Figure 8. This was also true for severely faulted joints or cracks. Lastly, Figure 9 illustrates the distinct reflection pattern of bridges, in contrast to that for the pavement.

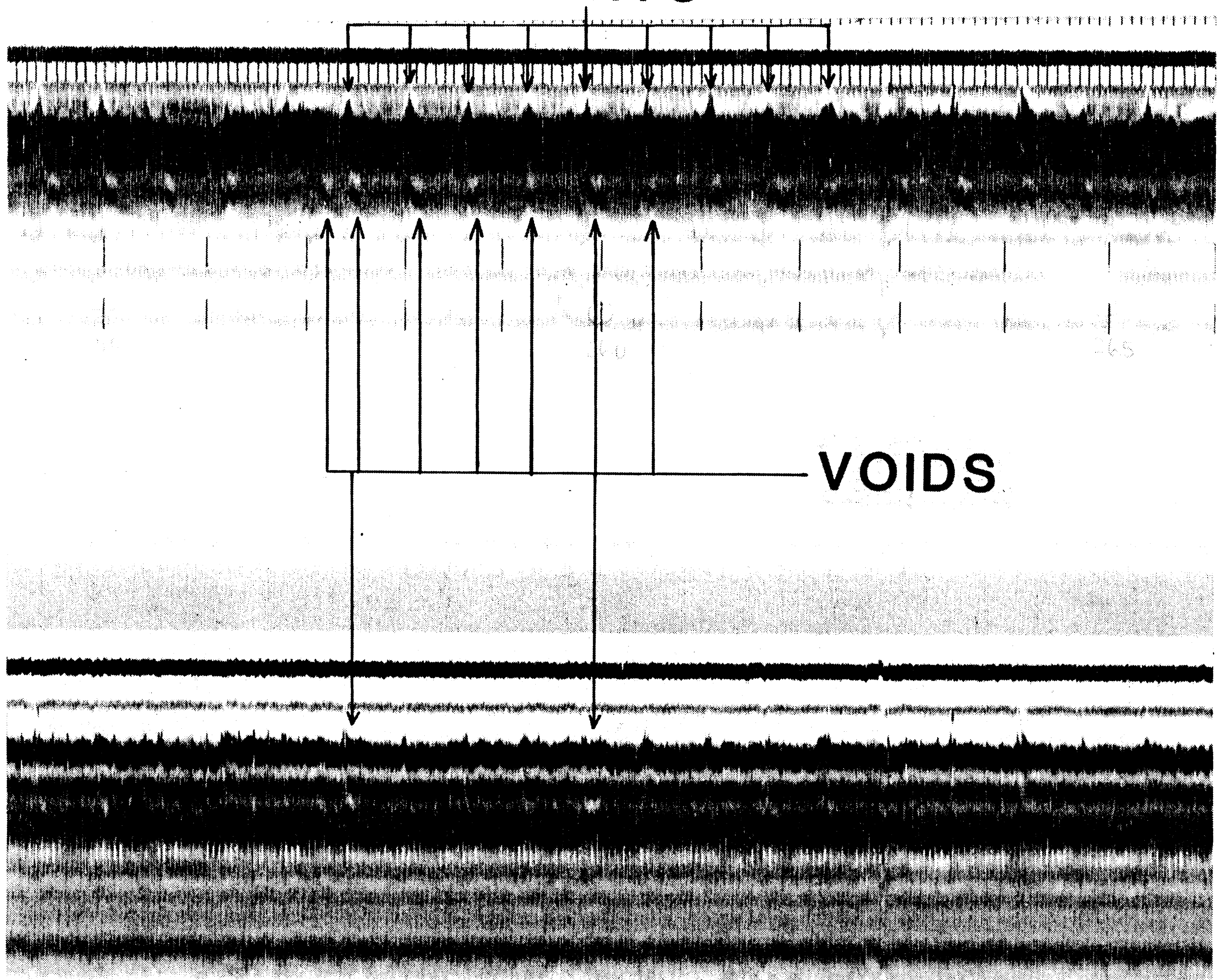

Figure 7. Reflection profile for the northbound travel lane of I-81 in Botetourt County, Virginia, at 25,400 to 26,600 ft from starting point.

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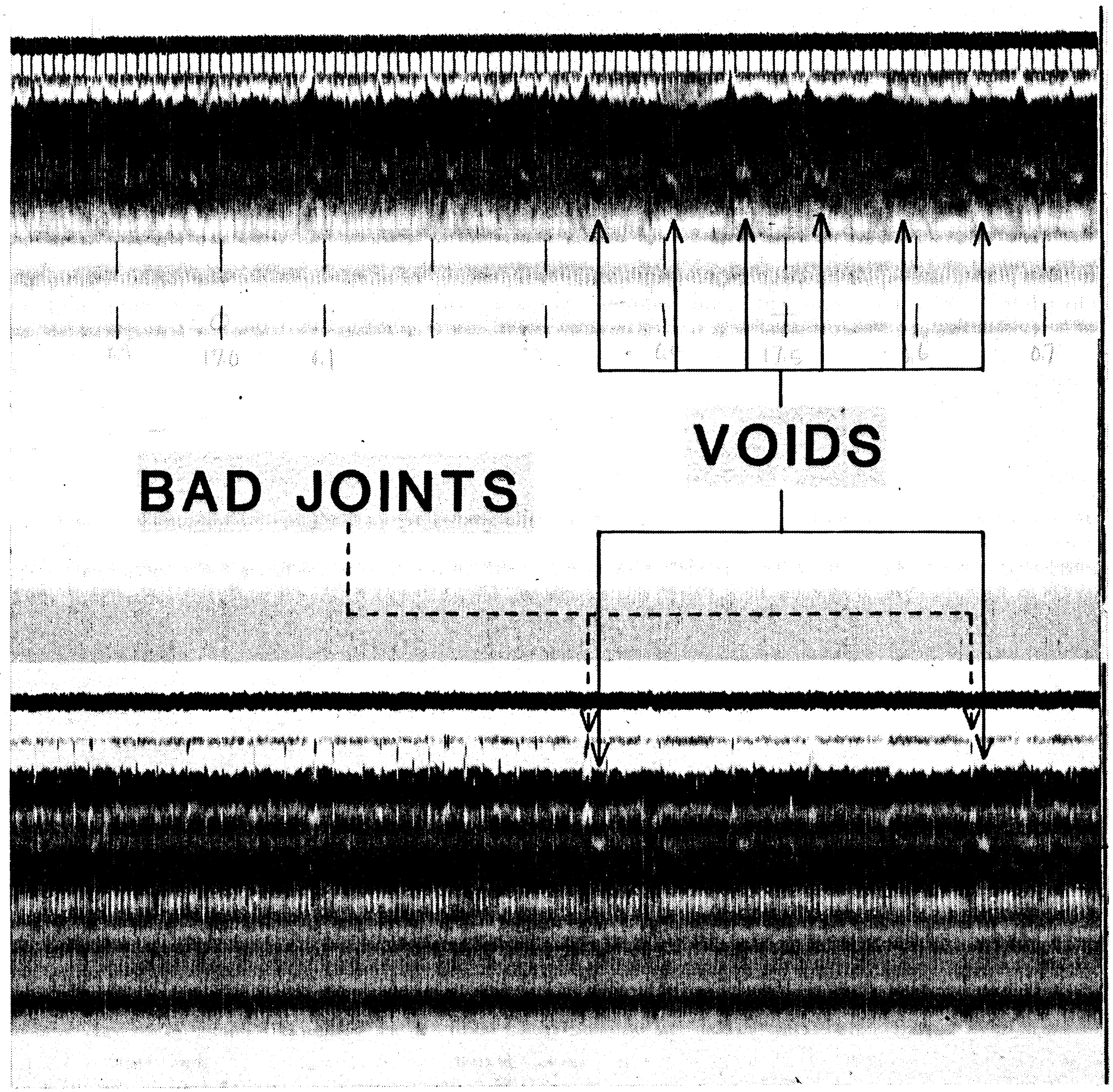

Figure 8. Joints with severely damaged sealant.

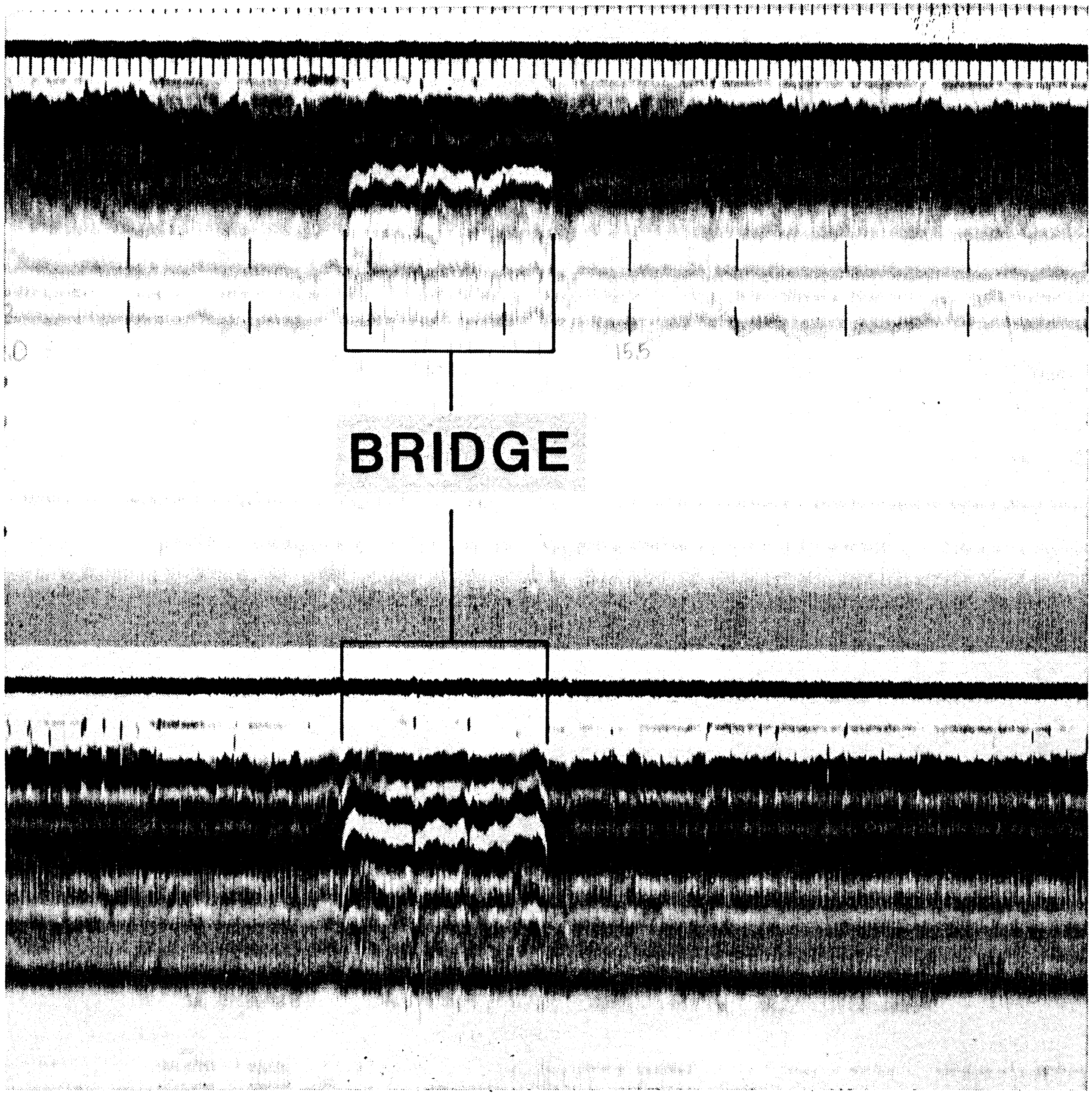

Figure 9. Characteristic reflection pattern for bridges.

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Figures 7 and 8 have demonstrated how radar can be very useful for the rapid, nondestructive detection of voids beneath a concrete pavement and also, to some extent, for the rapid assessment of the condition of joints. Other useful applications of radar and types of information derivable from its use are discussed later. The immediately following discussion concerns the first objective of this study, which was to evaluate the accuracy of radar for detecting and locating voids.

Detection and Location of Voids

Briefly stated, the detection and location of a void involves three steps: (1) the sensing of the reflection associated with the void by the radar unit, (2) the proper recognization (or interpretation) of this reflection by the operator or user, and (3) the location of the void, with respect to the entire pavement, by the location reference unit. Each of these steps can contribute an error affecting the overall accuracy of a pavement survey.

Since the error associated with the third step is probably the simplest to deal with it will be discussed first.

Error from the Location Reference Unit

In order to determine how reliable the location reference unit was, the distance (to the nearest foot) between each pair of consecutive reference markers in the southbound travel lane was measured. Each of these distances was then compared with the intended distance (or interval) of 1,000 ft so that the errors could be assessed.

The results, as shown in Figure 10, indicated that the actual distances between the reference markers were consistently greater than 1,000 ft. The errors, which assumed a normal distribution, ranged from 0 to 10 ft, with an average of 4 ft. These may have been caused by improper tire pressure in the fifth wheel and missed pulse counts by the optical encoder. This second source of error can be minimized by using an optical encoder that counts more than the 25 pulses/lin ft produced by the encoder used in this study and thus making occasional missed pulses less significant. It has also been suggested that mounting the fifth wheel at the center or at either the front or the rear of the survey vehicle instead of at the side would also minimize error.

If sealing the detected voids is planned, reference marks with errors of such magnitude as obtained in the study couldn't be used with confidence by maintenance crews for pinpointing each void. Fortunately, for jointed pavements such as the section of I-81 surveyed, this problem can be remedied by (1) associating each void with the slab that is above it, and (2) locating this void in terms of its distance from the upstream joint, or the beginning of the slab. This distance is then determined by subtracting the position of the upstream joint from that of the void, with both positions being measured with the location reference unit.

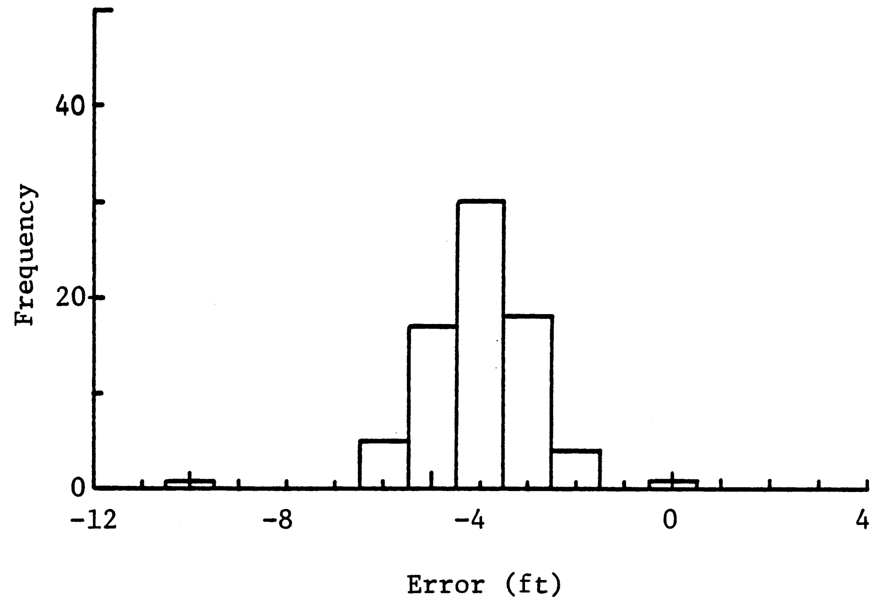

Figure 10. Observed errors in the location reference unit.

For future surveys, the reference marks can be spaced closer, say every 50 or 100 ft, so that any errors would be less significant. For continuously reinforced concrete pavements, using a short spacing between marks is the only recourse, since the above remedial procedure isn't applicable.

Error Associated with Interpretation of Reflection Pattern

The characteristic reflection pattern of a void is readily recognizable in a reflection profile, as previously illustrated in Figures 7 and 8. However, the reflection for a very shallow or small (in area) void may be so difficult to discern that it might be missed by an operator. This limitation, normally attributed to the instrumentation, contributes to the errors that affect the overall accuracy of the radar technique, which will be discussed in the next section.

Furthermore, the natural differences in perceptiveness among operators (assuming they have equal skill) may also cause some degree of difference (and therefore error) in their interpretations, particularly with analog data. This type of operator error is relatively difficult to assess.

In the analysis of a stream of reflection patterns for miles of pavement, human fatigue can also cause relatively large, though maybe infrequent, errors to occur. Specifically, this type of error involved sizeable voids detected by the radar but not recognized and listed by the operator. Such errors have, in fact, been observed during spot checks of reflection profiles for some sections of the pavement against a listing

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of the detected voids provided by the contractor. Because such errors are believed to be infrequent and limited, they were not assessed in this study.

Overall Accuracy of Radar in Detecting Voids

Cores were taken from the slabs to verify the presence of radar detected voids. The verification procedure is shown in Figure 11. If the core dropped >1/8 in, it was obvious that a deep void was present. If the core dropped $\leq$1/8 in, the hole was inspected for grout. If grout was found, it was obvious that the void had been filled with grout between the time the radar survey was conducted and the time the core was taken. If no grout was present, the hole was filled with water, and the quantity of water required to fill the core hole was measured. The volume of the void then was estimated by subtracting from the total volume of water used, the volume of water required to fill the hole in the slab and the volume that drained through the subbase material. As will be explained later, a volume of $\leq$0.005 ft^3 was not considered to be indicative of a void. If the water test did not indicate a void then the void condition was designated "uncertain."

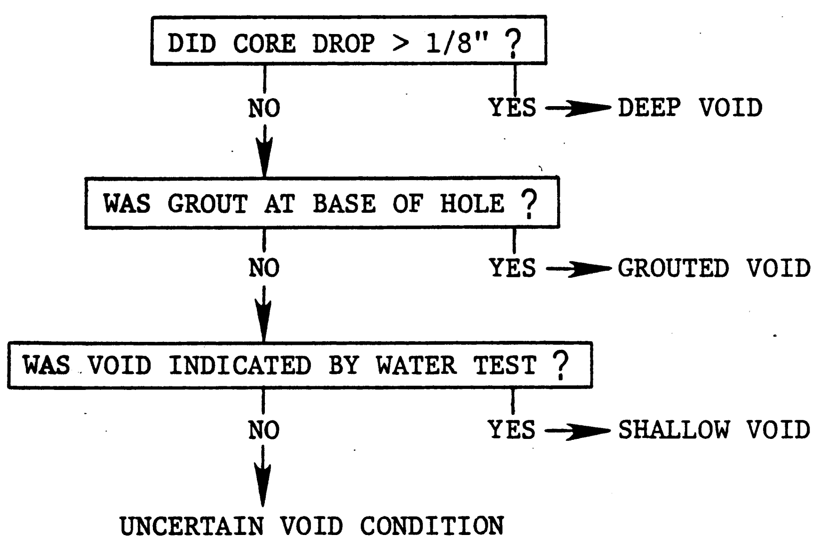

Figure 11. Determining void condition after coring.

It was difficult to precisely determine the quantity of water that drained through the subbase material. The method used was based on an assumption that the flow through the subbase was at a constant rate during the test period. For a constant flow rate the volume of water that flowed through the subbase was assumed to be equal to the volume of water in the core hole in the slab, which was approximately 9 in deep, multiplied by the time required to fill the subbase, void, and core hole and divided by the time required for the water to drain from the hole in the slab. Typically, from 10 to 30 seconds were required to fill the subbase, void, and core hole in the slab, and 5 minutes were required for the water to drain from the core hole. An evaluation of the permeability of the subbase revealed that when the subbase consisted of a 2-in layer of sand over CBR 30 material, the permeability coefficient was approximately 10^{-3} cm/sec. Therefore, the error in estimating the flow through the subbase was negligible, because of the small amount of water that flowed through the subbase during the test. In areas where there was no sand over the CBR 30 material, the permeability coefficient was approximately 10^{-1} cm/sec. For this condition if the CBR 30 material was not saturated prior to the water test, it could absorb as much as 0.3 lb of water, which amounts to a volume 0.005 ft^3. All but one void identified by the water test had a volume in excess of 0.005 ft^3. Therefore, the test method was reliable for the project conditions.

Table 2 shows the void condition at the locations that were cored. The detailed radar analysis included corrections for errors from the location reference unit and interpretation of data. In the second column, it can be seen that 103 cores were taken. This column also shows that, unfortunately, at 28 locations there was uncertainty as to whether or not there was a void. As can be seen in column (3), at only 10 of these locations did the radar indicate that a void existed. Again referring to column (1), at the 75 locations for which the void condition could be determined by coring, a shallow void was found at 39 locations, a deep void at 29, and grout at 7. It is obvious from these data that the radar survey had a high rate of success when the voids were deep. In fact, 26 (or 90%) of the 29 deep voids were located by the radar. On the other hand, it identified only about half (21 of 39) of the shallow voids. Thus, as would be expected, the survey showed that radar is more likely to miss small or shallow voids as compared to large or deep voids. Using the 75 locations for which the void condition could be determined by coring, it can be seen that, overall, radar found confirmed voids 68% (51 of 75) of the time.

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TABLE 2

Void Conditions Determined by Coring and Radar

Condition Based on Coring		Condition from Detailed Radar Analysis	
Condition (1)	No. of Cores (2)	Voids (3)	No Voids (4)
Uncertain	28	10	18
Shallow	39	21	18
Deep	29	26	3
Grout	7	4	3

Estimation of Quantity of Grout

Slab stabilization is increasingly being recognized as a potentially effective way to restore support to a concrete pavement, when voids beneath the slab are the major cause of distress. Estimating the quantities of grout needed for a stabilization operation has been quite difficult. Reported attempts to correlate initial pavement deflections and the volume of grout pumped have not been successful.(10) As a last recourse, various historical averages of quantities of grout per grout hole have been used, even though this approach lacks any scientific basis.

It is the belief of the authors that the radar survey technique has the potential to provide a more sound basis for estimating grout quantities from the extent of detected voids. Consider that, theoretically, the total quantity of grout used (say, in a day) should be equal to the total volume of all the voids beneath the slabs grouted; i.e.,

$$G = \sum V_i \quad , \tag{4}$$

where

G = quantity of grout, in ft^3,

V = volume of individual void, in ft^3, and

i = 1, 2, 3.... nth voids.

Unfortunately, it is not known what geometrical shape(s) (as viewed from the top of the pavement) these voids usually assume. It is conceivable that they could assume different shapes (some definable and others undefinable) or that, in a simple case, a majority could assume the shape of a rectangle, a triangle, or a combination of both. To simplify this discussion, assume that each void is practically a rectangle that can be defined by a width, W_i, and a length, L_i. And, together with a depth, D_i, the total volume could be expressed so that equation 4 becomes

$$G = \sum W_i L_i D_i \quad . \tag{5}$$

This implies that if the three independent variables can be measured by radar with some reasonable degree of accuracy, then it should be possible to arrive at a reasonably accurate estimate of the quantity of grout needed to fill the voids.

Unfortunately, the presently used radar has two limitations that prevent the adoption of this rigorous approach. First, the radar is limited in its areal coverage. This limitation is illustrated in Figure 12, which shows an actual void that had been filled with grout then exposed by carefully removing the entire concrete slab. In this example, only about 40% of the void, the area directly below the coverage (or path) of one of the two antennas, would be detected. And, only its length could be defined or measured. This limitation can be easily eliminated by building a radar system with the capability to simultaneously use three, or even four, antennas. With such a system, both L_i and W_i could be measured.

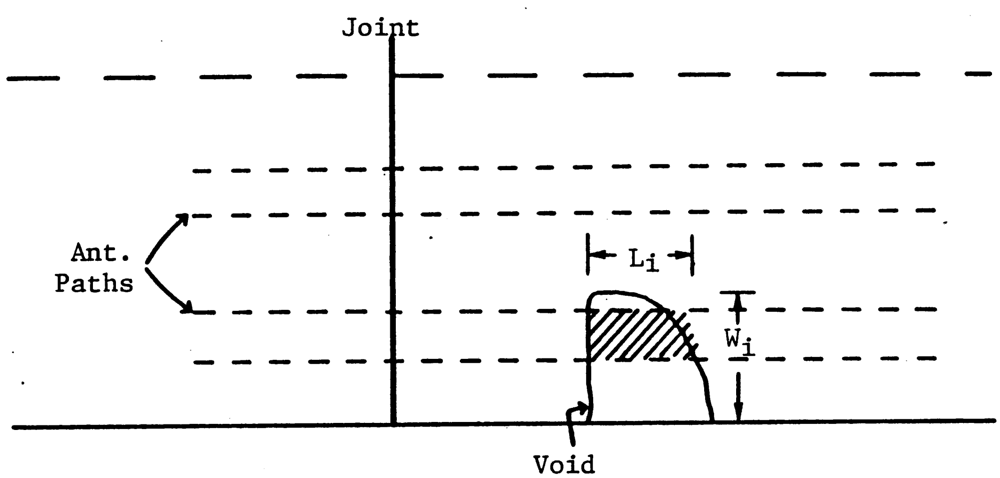

Figure 12. Limitation on coverage by radar. Only the shaded portion of this actual void would be detected and defined by radar.

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The second limitation concerns the determination of depth. As discussed earlier, most voids are no deeper than a few eighths of an inch, so that the reflection from the bottom of a void (P3) would be overlapped by the reflection from the bottom of the slab (P2). This means that it would be extremely difficult, if not impossible, to estimate the time separation between these reflections so that the depth of a void could be calculated from equation 3. This problem can be remedied by utilizing the existence of a linear relationship between the amplitude of P3 and the void depth. This approach, however, also entails difficulty since it requires that a reasonably good correlation between these two variables be established by coring the pavement above a sufficient number of properly selected voids of various depths.

It is obvious that there is not sufficient information on void width and depth to enable the use of the rigorous approach outlined in equation 5, and that a simpler version of this should be attempted.

Correlation of Grout Quantity with Length of Void

For a simpler version of equation 5, assume (1) that the depths of all voids are practically uniform, i.e., constant, and (2) that the widths of all voids also are practically constant. It is obvious that the first assumption would be more acceptable than the second. Nevertheless, with these assumptions equation 5 becomes

$$G = WD \sum L_i = C + k \sum L_i \quad . \qquad (6)$$

In order to determine the utility of this approach, the daily quantities of grout pumped under various sections of some 14.7 lane miles of the northbound lane during 22 days of slab stabilization operations were measured (Table 3). These daily quantities were then correlated with the total length of voids (in linear feet) detected by the radar survey to be underneath the slabs that were subsealed each day. (The pattern of grout holes used is shown in Figure 13.)

As Figure 14 shows, there was only a 51% correlation between the lengths of the voids detected by radar and the quantities of grout used. It appeared that the correlation suffered where the void lengths were low, as evident in the scattering of data points. It is interesting to note that when the regression line is used to estimate the quantity of grout needed for each of the 22 days, based on the data on the lengths of voids, and the 22 estimated individual grout quantities from Table 3 are summed, the resulting estimated total amount of grout needed for the entire grout operation was equal to the total amount of grout actually used (1,022 ft^3). This finding indicated that the scattering of data points at the low end of the regression line was very even.

The following should be noted.

1. Any void in the area between the two antenna paths (Figure 5) obviously would not have been detected and therefore was not included in the estimation of the total extent of voids, even though the void would be grouted.

2. Some of the detected voids were a considerable distance from joints, so they would be missed by the grout holes and not be filled.

3. There was a strong belief that more grout than was needed was pumped under some slabs, even though the construction crew took care not to lift the slabs.

TABLE 3

Quantities of Grout used and Quantities Estimated from the Length of Voids Detected by Radar

Date	Length of Voids (lin ft)	Quantity of Grout (ft^3) Used	Estimated
7/12/85	293	48	59
7/13/85	351	62	64
7/15/85	408	64	68
7/16/85	66	71	43
7/17/85	18	38	40
7/18/85	0	12	38
7/22/85	31	58	41
7/23/85	344	65	63
7/24/85	162	47	50
7/29/85	16	38	40
7/30/85	56	32	42
7/31/85	23	37	40
8/01/85	3	7	39
8/02/85	52	53	42
8/03/85	75	44	44
8/05/85	53	79	42
8/06/85	123	53	47
8/07/85	107	49	46
8/12/85	19	43	40
8/13/85	8	26	39
8/14/85	120	44	47
8/15/85	131	52	48
	TOTAL	1,022	1,022

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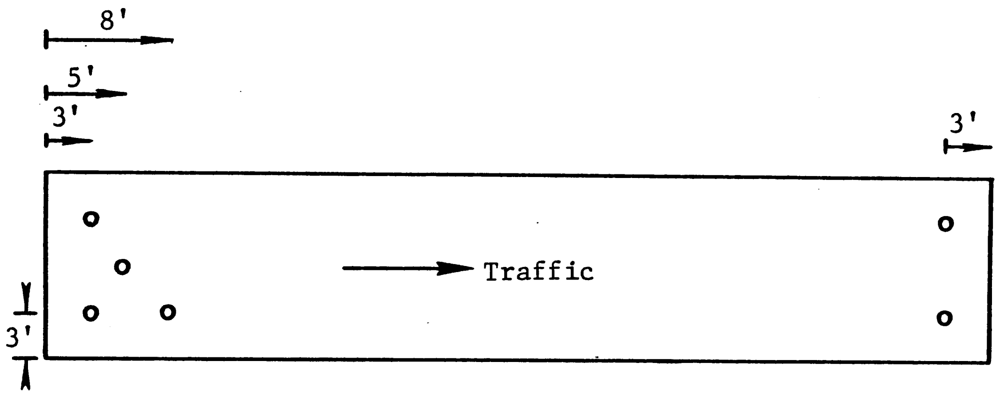

Figure 13. Grout-hole pattern used in slab stabilization.

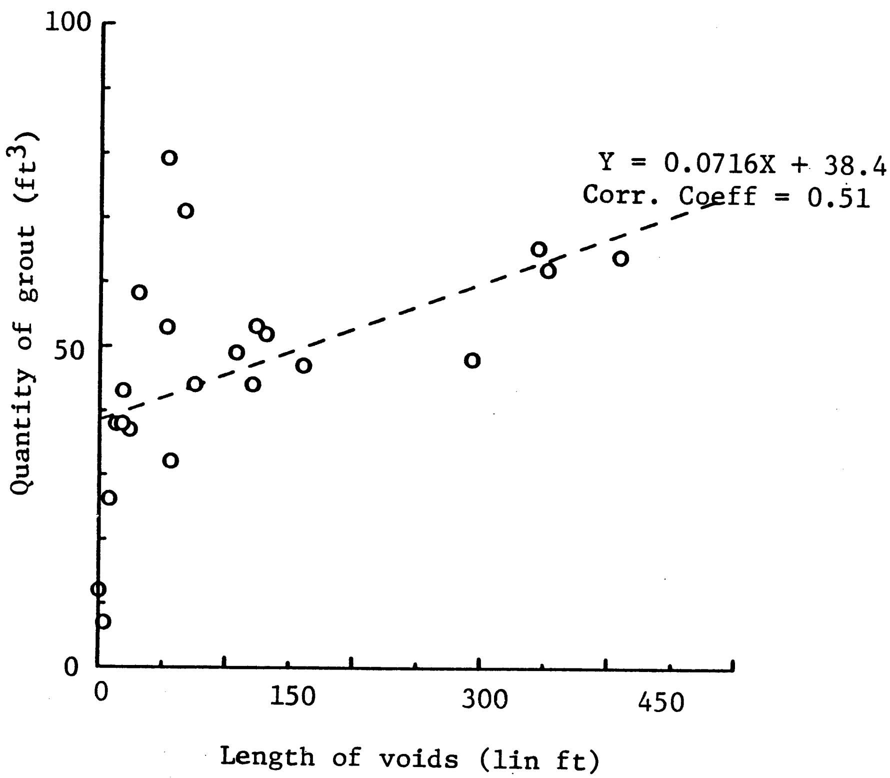

Figure 14. Correlation between length of voids and grout quantity.

It is difficult to assess how much these three factors affected the correlation; nevertheless, they cannot be ignored, especially in regard to voids of short length. Lastly, although the correlation was relatively poor, statistical tests indicated that the regression line was significant at the 95% probability level. This indicates that the rigorous approach toward the estimation of grout quantities expressed in equation 5 would be even more successful and should be tried as soon as the necessary three- or four-antenna radar units become available. Such units can provide a convenient, better definition of the spread, and therefore estimate of the width, of a void than can the two-antenna radar unit used in this survey. (The depth of each void could probably then be assumed to be constant, say at one-eighth to one-quarter of an inch, without significantly affecting the result.)

Other Uses of Radar Survey

Checking the Effectiveness of a Grouting Operation

So far the discussion has dealt only with the use of radar for detecting and locating voids underneath the pavement slabs prior to pavement rehabilitation and restoration. Radar, however, can also be used after the repair to check if the grouting operation was effective.

Figure 15 shows the reflection profile for a portion of the pavement that was covered in the radar survey and also happened to have been grouted during a preceding maintenance season. As is evident in this example, there was a sufficient difference between the dielectric properties of the grout and those of the base material for the presence of grout to be detected. More important, the profile also shows signs of voids for both antenna paths. It is possible that the voids had been missed in the grouting operation or had formed subsequently. Also, there were two joints that were likely to be defective; one happened to be next to the voids, while the other was only one slab (61.5 ft) away.

Designing Effective Grout-Hole Pattern

At the beginning of a slab stabilization project, a pattern for the grout holes is selected based on engineering judgement, and depending upon the results being obtained during the course of the project, this may be changed. The selection is not easy, since at least four different patterns are available and there often isn't enough information on the voids underneath a pavement upon which to base the decision.

The information on the location of voids that radar provides can be very useful in this selection process. To illustrate, consider some of the radar results obtained for the southbound lanes of I-81, that have yet to be rehabilitated. For some 13,000-ft sections of the southbound travel lane, where most voids were located, Figure 16 shows that, in general, a majority of the voids were centered around the joints for both wheel paths. At the 3-ft wheel path, 88% of the voids were centered

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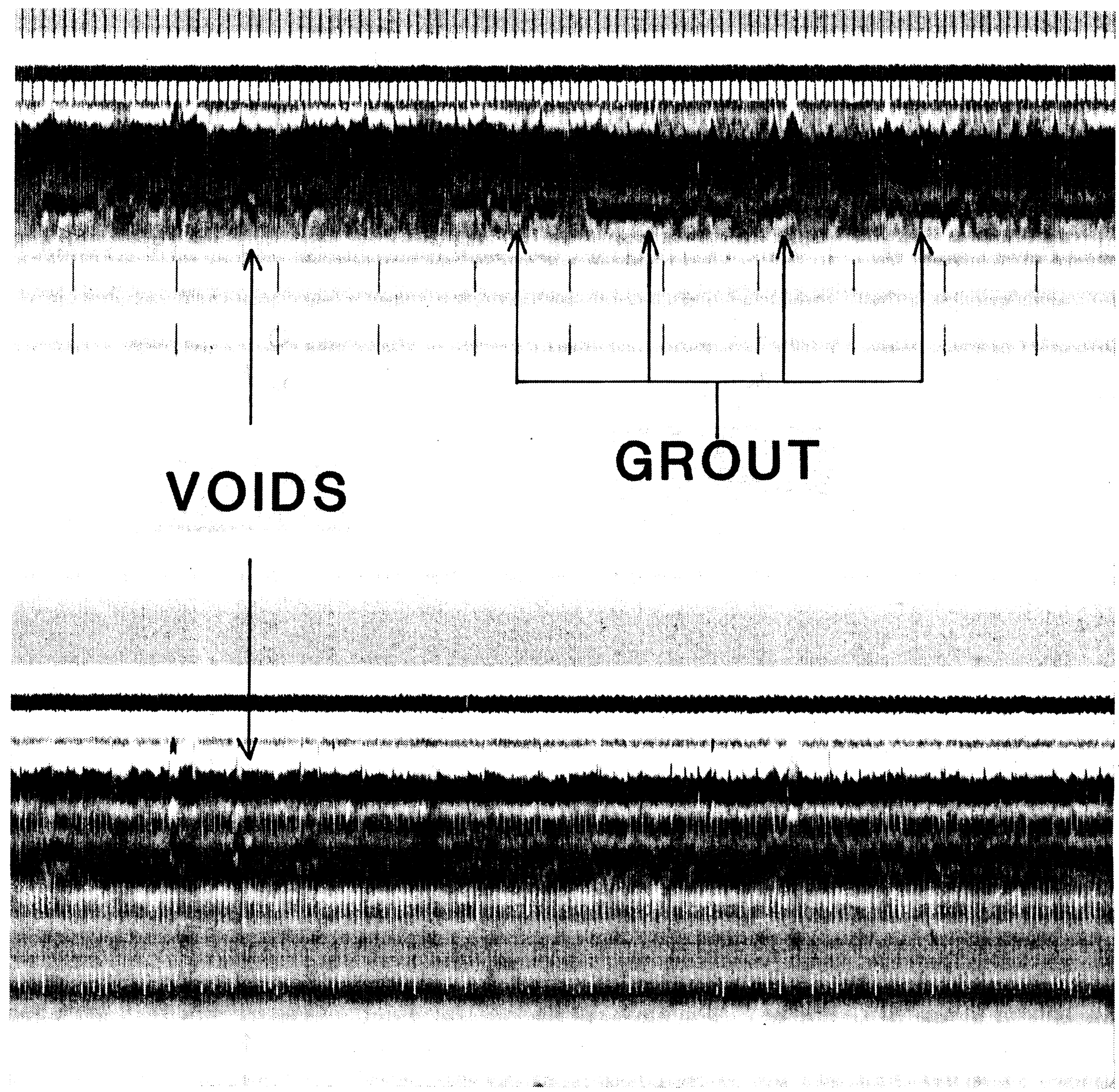

Figure 15. Reflection profile for a portion of a grouted concrete pavement, showing grout and voids.

within 7 ft downstream of a joint, 4% were centered within 2 ft upstream, and only 8% were relatively far from a joint. At the 8-ft wheel path, 66% of the voids were centered within 4 ft downstream of a joint, 13% were centered within 2 ft upstream, and 21% were relatively far from a joint.

A further analysis can provide clues on how effective a specific hole pattern would be if used in filling these voids. Consider the use of the same six-hole pattern illustrated in Figure 13, and assume that if a grout hole falls no farther than 1 ft from either end of a void, this void would be effectively filled by grout pumped from that hole. Also assume that the two top holes in this pattern coincide with the 8-ft wheel path, while the three bottom holes coincide with the 3-ft wheel path, thus allowing for some reasonable drifts around these intended wheel paths during the survey. Based on these assumptions, the relative effectiveness of each of the grout holes except the middle one can be assessed by determining the percentage of voids that grout pumped from that hole would fill.

Based upon the analysis of 103 slabs, it was determined that holes #4 and #5 would fill approximately 78% and 14%, respectively, of the voids found below the 3-ft wheel path (see Figure 17). Of course, there would be some degree of overlapping between these two holes, since some voids in that area were longer than the 5-ft distance between these two holes. Hole #3 would cover another 8% of the voids. More important, approximately 18% of the voids would not be sealed from any of these three holes, simply because these voids, being further away from the joints, couldn't be reached by these holes alone. Similar conclusions can be drawn concerning the effectiveness of holes #1 and #2, which covered 16% and 59%, respectively, of the voids. No conclusion can be made on the effectiveness of hole #6, since no radar data had been obtained for that vicinity.

It is clear that if either of these patterns were used for all slabs in this southbound travel lane of I-81, a small percentage of the voids would likely not be filled, since neither pattern would be fully effective by itself. Although it may entail extra effort, an ideal approach would be to treat each slab individually by customizing the locations of grout holes according to radar data obtained for each slab. For maximum effectiveness, at least a triple-antenna radar system that was discussed earlier should be used.

The data for the same 103 slabs can be analyzed from a different standpoint as illustrated in Figure 18, which shows the number of a particular grout hole that would coincide with a void. In the 8-ft wheel path only 5 of the #1 holes and 19 of the #2 holes would hit or coincide with a void. The highest frequency of a hole coinciding with a void would occur at the #4 hole in the 3-ft wheel path. At this location 76 of the 103 holes would coincide with a void. Also, note that between the

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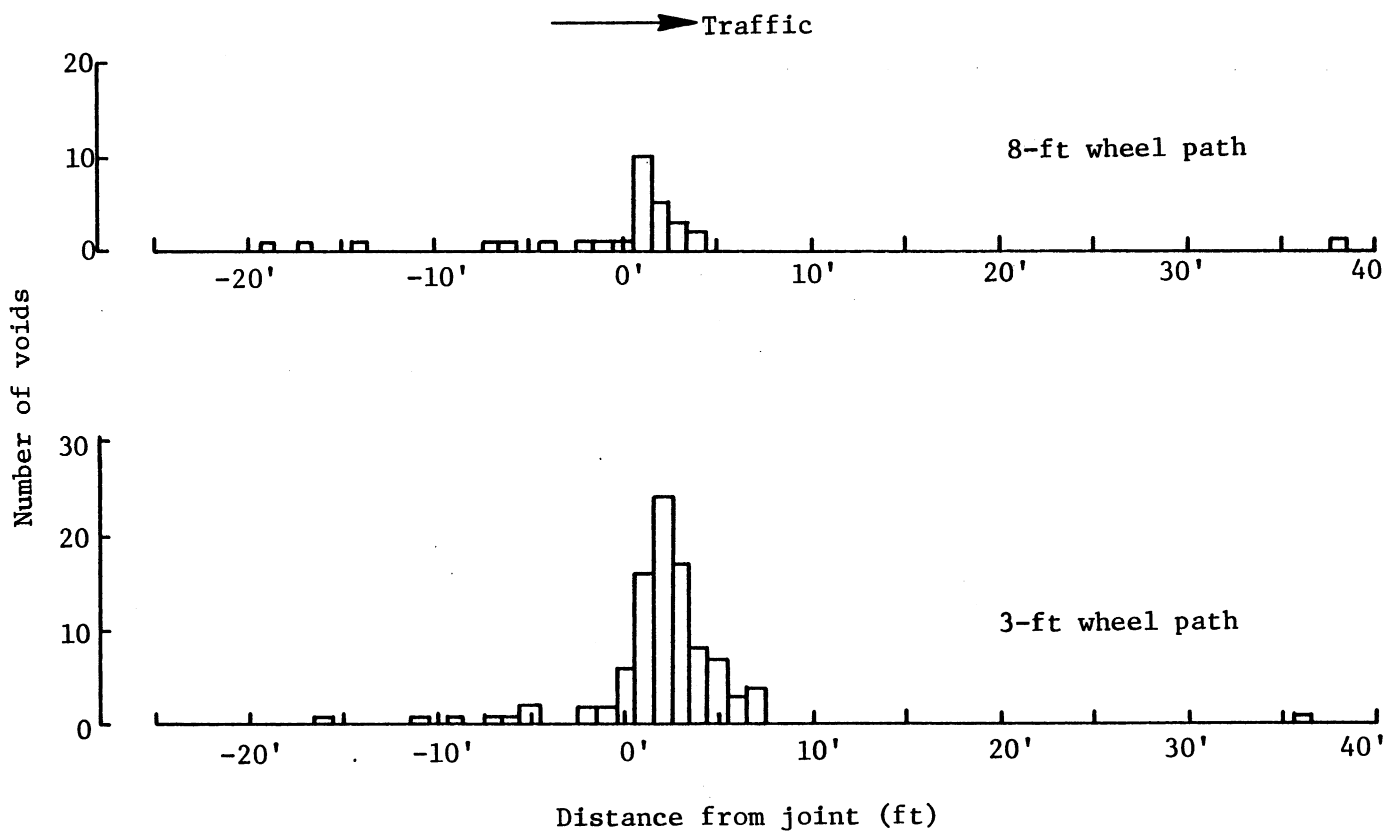

Figure 16. Distribution of the centers of the voids detected by radar in the southbound travel lane of I-81.

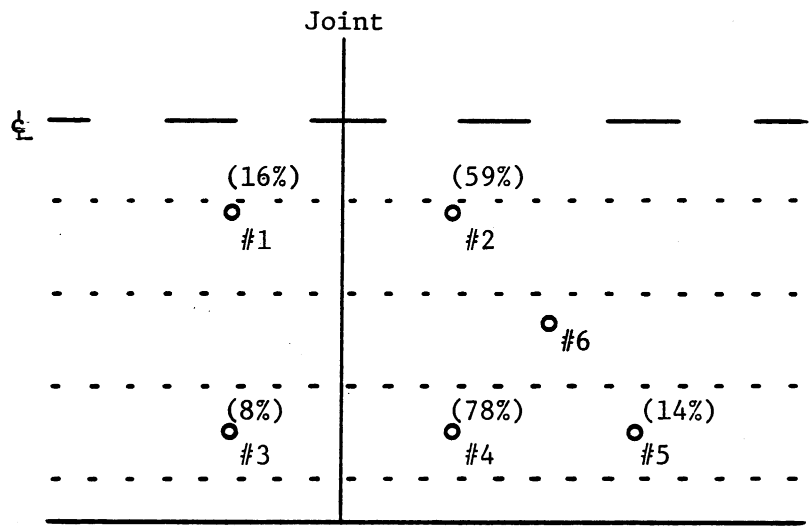

Figure 17. Various percentages of voids that would be sealed from a six-hole pattern.

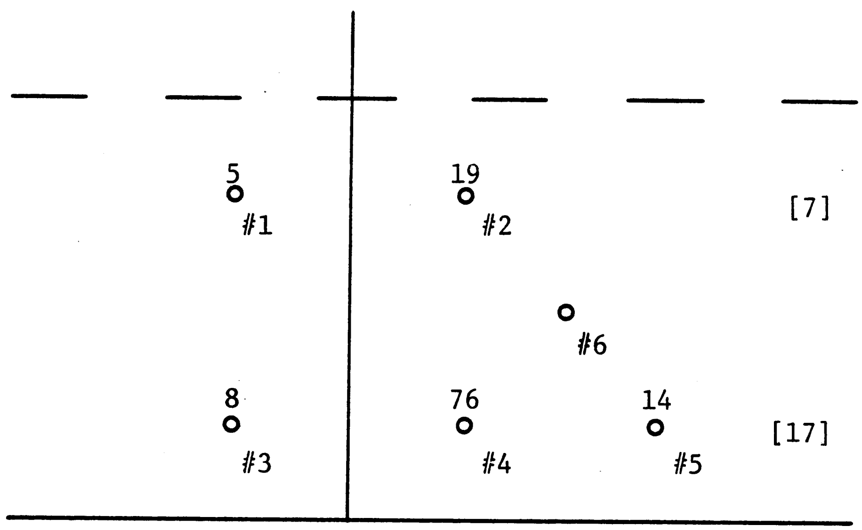

Figure 18. The number of each of the 6 standard grout holes coinciding with a void for 103 slabs. The bracketed numbers represent the number of voids in their respective vicinities that would be missed by the grouting operation.

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grout holes at each end of the slabs, 7 voids in the 8-ft wheel path and 17 voids in the 3-ft wheel path would not receive grout. It is obvious that, at a cost of $8.40 per hole, equating to $63,000 for the 14.5 lane-miles, it would have been cost-effective to prepare the grouting contract based on the results of a radar survey that cost only $6,000 for 14.5 lane-miles. This analysis indicates that money can be saved by preparing a slab stabilization contract around the results of a radar survey rather than grouting all slabs using a standard hole pattern.

Miscellaneous Uses

Other interesting information can be derived from the radar survey conducted on I-81. An example is illustrated in Figure 19, which shows the size distribution of voids detected by radar in the two southbound lanes. These log-normal distributions indicate that there were ten times more voids in the travel lane than in the passing lane. (Similar types of distributions were observed for the northbound lanes, except that in the travel lane there were only four times more voids than in the passing lane.) Such a disparity between the extents of voids occurring underneath a travel lane as compared with a passing lane has also been inferred from reported deflection measurements made on concrete pavements. This disparity arose from the fact that travel lanes, in general, carry more traffic than passing lanes.

Although not investigated in this survey, radar may also be useful in detecting poor drainage in a subbase, which is another cause of pavement distress. Moisture accumulation in a localized area in the subbase would cause the material there to have a higher dielectric constant and attenuation than its surroundings, and thereby allow for its detection by GPR.

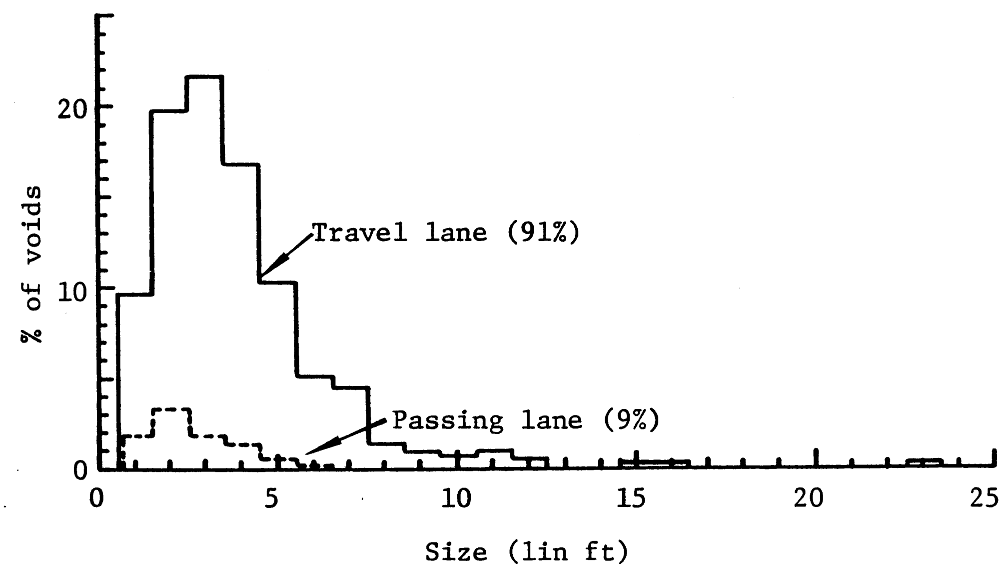

Figure 19. Size distribution of voids detected underneath southbound lanes of I-81.

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CONCLUSIONS

Based on the preceding discussion, the following conclusions can be drawn.

1. A complete survey can be carried out at a minimum rate of 5 lane miles of pavement per hour, with a very minimal interruption of traffic.

2. The location reference unit used by the contractor in conjunction with his radar unit didn't provide sufficient accuracy, which should probably be no less than ±1 ft.

3. To minimize analysis time and errors, complete computerization of the interpretation of recorded reflection patterns would be desirable.

4. As compared to data corrected for errors in the location reference unit and the interpretation of radar. cores taken from the slabs showed that the radar found known voids 68% of the time. As expected, radar found deep voids (>1/8 in) 90% of the time and shallower voids only 54% of the time.

5. Despite this deficiency, most of which can be eliminated with further development of the radar technology, GPR can already be used as a rapid nondestructive tool for surveying concrete pavement for underlying voids.

6. A regression analysis of data on daily grout quantities versus total linear feet of detected voids yielded a less than desirable degree of correlation (51%). This finding indicates that grout quantities cannot be estimated from linear feet of voids detected with reasonable accuracy.

7. However, the regression was statistically significant at the 95% probability level. This indicated that the more rigorous approach of estimating grout quantity that uses additional parameters (width and depth of voids) as expressed in equation 5 potentially can be more successful. The width of each void can be estimated easily when a three-antenna (or even a four-antenna) radar system is used, and then the depth can be assumed to be practically constant.

8. Radar surveys can be very useful not only in detecting and locating voids before planning the stabilization of a concrete pavement, but also for checking on the effectiveness of completed stabilization.

9. Radar surveys also provide information useful in deciding where to pump the grout for a cost-effective slab stabilization operation.

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RECOMMENDATION

This study has demonstrated that ground-penetrating radar can be very useful in the inspection of concrete pavements. In view of this, it is recommended that radar be integrated with other useful pavement inspection tools into an inspection system for use by the Virginia Department of Highways and Transportation.

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