EVALUATION OF OVERLAID BRIDGE DECKS WITH GROUND-PENETRATING RADAR

by

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(The opinions, findings, and conclusions expressed in this report are those of the author 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)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

February 1982
VHTRC 82-R42

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ABSTRACT

There is an urgent need for methods that can be used to rapidly and nondestructively determine the condition of an old concrete deck beneath an asphaltic concrete wearing course. In recognition of this need, the technique of ground-penetrating radar was investigated.

In practice, microwave-frequency impulses of about 1.1 nanosecond pulse width are transmitted into an overlaid bridge deck by a radar transducer that also serves as a receiver. When these electromagnetic pulses are directed through a delaminated concrete area, there is some pulse reflection from the deteriorated concrete, (the more severe the delamination, the more pronounced the reflection), in addition to the normal reflections at the air-asphaltic concrete and asphaltic concrete — portland cement concrete interfaces and the reinforcing steel. The reflected pulses are then picked up by the transducer and transformed into the audio frequency range by a time-domain sampling technique and displayed on a facsimile graphic recorder as a pulse reflection profile.

Although intended for use on overlaid bridge decks, the technique was experimentally used on three non-overlaid concrete decks and two old concrete deck slabs, in addition to three overlaid decks. To obtain 'ground truths' for comparison, conventional soundings were performed on the non-overlaid decks and slabs and two of the overlaid decks after their overlayments were removed. The results showed that ground-penetrating radar can be used successfully to detect concrete delaminations in both non-overlaid and overlaid bridge decks, since the delaminations are manifested in the recorded radar pulse reflection profiles as recognizable irregularities in the reflection bands corresponding to the top mat of the reinforcement. These irregularities, or signatures of concrete delaminations, were often in the form of depressions, but in some instances appeared as blurs or breaks in the profiles. It was also found that the radar sometimes missed small delaminated areas of about 1 ft. (0.3 m) width and less. However, this relatively small deficiency does not impair the overall effectiveness of the technique as a nondestructive inspection tool for both types of decks.

The experimental procedure can be used as is to inspect decks, if lane closure is not a major concern. However, with little further experimentation, this requirement may be completely eliminated.

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INTRODUCTION

The deterioration of concrete bridge decks, mostly induced by corrosion of the reinforcing steel, is probably the most perplexing problem confronting bridge engineers. Faced with the high projected costs for repairing the deteriorated decks and a severely reduced budget, the engineers now more than ever need data from routine deck condition surveys to aid them in the assignment of priorities and scheduling of maintenance. Such surveys can be relatively expensive, however, because the presently used methods for detecting concrete delaminations are laborious and require lane closure, so there is a consequent need for a rapid and nondestructive technique for determining the general condition of bridge decks by locating delaminated areas. The technique would be even more valuable if it could locate delaminated concrete areas in an overlaid bridge deck, for which present methods are even less suited.

BACKGROUND

The most commonly used simple devices for locating delamination in concrete decks that are not overlaid with bituminous concrete are hammers, iron rods, and chains.(1,2) When these devices strike or are dragged over, as the case may be, a delaminated concrete, a distinctive hollow sound is produced on delaminated areas. Unless there is some interfering noise from nearby traffic, these devices, although subjective, are fairly reliable and will give detailed delineations of delaminated areas.

The Delamtect,(3) a commercially available, portable electronic instrument that works on the same principle as the above devices, utilizes hydrophones to sense the hollow sound and thereby eliminates any subjectiveness associated with the use of hammers, rods, or chains. The reliability of this instrument, however, is often questionable. All of these sounding methods are, to varying extents, time-consuming and require lane closures.

For surveying the condition of decks that have been overlaid, the sounding devices are even less satisfactory, as the bituminous concrete masks the sound of delaminations. Furthermore, when the sounding indicates a subsurface discontinuity, it is not known if the discontinuity is a delamination in the concrete deck or a faulty bond between the overlay and concrete.

This lack of a satisfactory nondestructive testing method has forced reliance upon coring, partial removal of the overlay, or examination of the underside of a deck, none of which provides sufficient information for the proper selection of rehabilitation procedures. Since a significant percentage of the bridge decks in the nation's highway network have now been overlaid with bituminous concrete and many are showing progressive signs of distress, a recent National Cooperative Highway Research Program synthesis report stated that "Methods that will quickly and nondestructively determine the condition of the concrete beneath an asphalt concrete wearing course are urgently needed."(2)

The experimental application of infrared thermography on uncovered concrete decks, by this investigator and others,(4,5) has indicated that under appropriate survey conditions the technique is very promising as a method for rapidly and reliably delineating delaminations and potentially suitable for rapid condition surveys. However, this investigator believes that if used on overlaid decks infrared thermography would have the same drawback as the other methods in being unable to differentiate between delaminations in the concrete and faulty bonds between the overlay and concrete.

In recognition of the need for a rapid and nondestructive inspection technique suitable for overlaid decks, this investigator scrutinized all potentially applicable nondestructive inspection techniques being used in industry and concluded that ground-penetrating radar had the best potential. This belief was given credence by a recent report describing an ongoing effort in New York City involving the experimental application of ground-penetrating radar for examining an overlaid deck. The report stated that "the results are promising" and that the technique "has a reasonable confidence level for identifying good or deteriorated concrete."(6)

OBJECTIVE

In view of the foregoing observations, an investigation was conducted to (1) ascertain the applicability of ground-penetrating radar for surveying the condition of overlaid bridge decks; (2) determine the limitations and advantages of the technique; and

(3) determine the type of development needed to bring the technique to the status of a routine inspection method.

PRINCIPLE OF GROUND-PENETRATING RADAR

Ground-penetrating, or downward-looking, radar came into existence in the late sixties. Since then, this technique has been put to a variety of uses, including locating buried cables, pipes, and sewer lines; examining the subsurface of the moon; and determining the thickness and structure of glaciers. Its potential application in the evaluation of airfield pavements has been studied;(7) its use for locating undermining in concrete sidewalks has recently been reported;(8) and, in ongoing studies, it is being used to locate voids beneath pavements,(9) and to determine the thickness of asphalt pavements.(10)

In practice, the radar, which uses a transducer for both transmitting and receiving, transmits microwave-frequency impulses into concrete, masonry, earth, or any nonmetallic materials under investigation. As Figure 1 illustrates, when the electromagnetic pulses strike the first interface (the surface), a portion of the pulse energy, depending on the dielectric properties of the material, is reflected and the remainder penetrates the material and traverses it at a velocity that is also dependent upon the dielectric properties of the material. This remaining pulse strikes another interface and part of it is reflected. The part not reflected penetrates the second interface, and the propagation process repeats again, if there are additional interfaces, until the pulse energy is completely dissipated. The reflected pulses are picked up by the transducer and transformed into the audio frequency range by a time-domain sampling technique. The resulting low frequency replica of the received signal is then amplified and further conditioned, and recorded on an oscilloscope as a composite waveform; and it can be displayed on a facsimile graphic recorder as a depth profile as illustrated in Figure 2. The dark bands correspond to the positive and negative signal peaks, and the narrow white lines are the zero crossings between peaks.

The shape of a composite waveform is characterized by the amplitude and time of flight of each reflected pulse. These parameters are, in turn, dependent upon the nature of the reflecting interfaces and the materials involved. To illustrate this point, consider the behavior of electromagnetic pulses at the interface between two media. The reflected pulse energy, E_r, is related to the incident energy, E_o, by the relationship

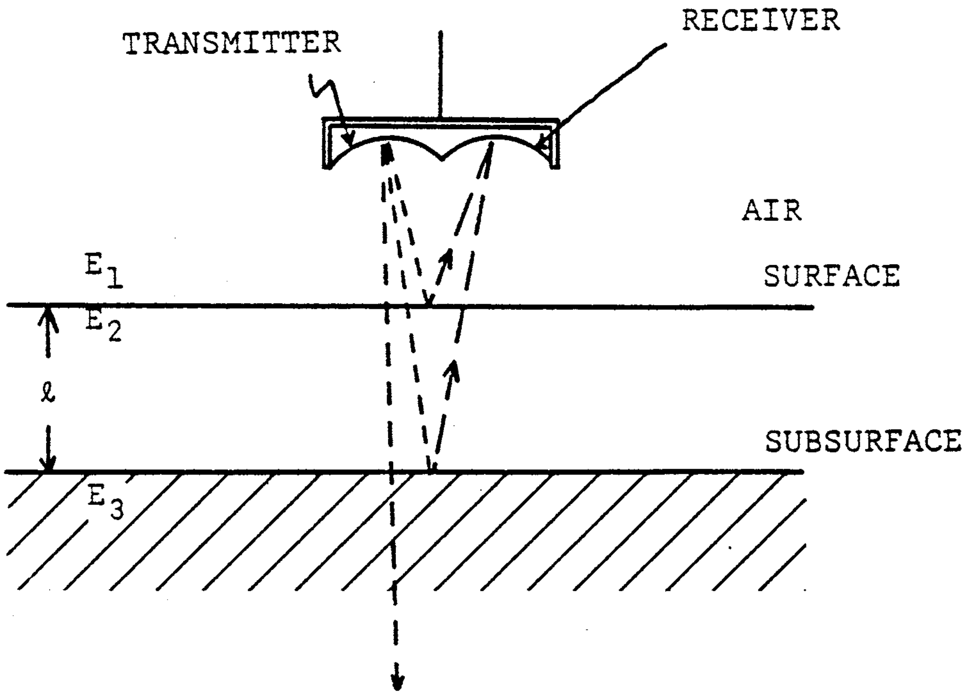


Figure 1. Transmission of radar pulses through a nonmetallic material.

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

where

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

$\varepsilon_1, \varepsilon_2$ = the relative dielectric constants for materials 1 and 2, respectively.

For the first interface depicted in Figure 1, which is air-material, equation 1 simplifies to

$$P_{12} = \frac{E_r}{E_o} = \frac{1 - \sqrt{\varepsilon_2}}{1 + \sqrt{\varepsilon_2}}, \tag{2}$$

since $\varepsilon_1 = \varepsilon_{air} = 1$. After each reflected pulse is matched to its corresponding interface, the thickness, or depth (D_m), of any given layer of subsurface material (m) through which the pulses have passed is given by

$$D_m = \frac{t_m V_m}{2} = \frac{t_m C}{2\sqrt{\varepsilon_m}}, \tag{3}$$

where

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

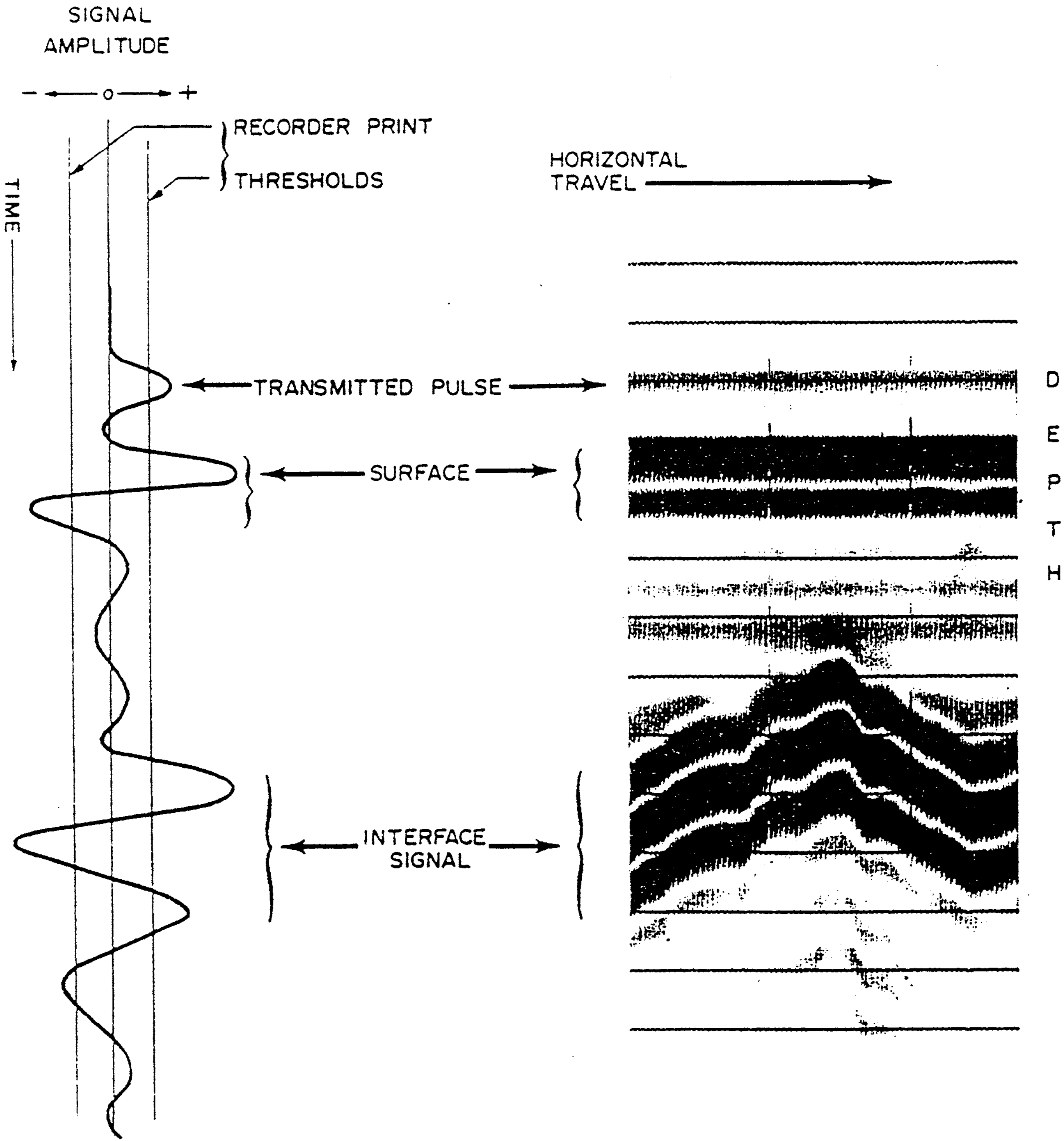
V_m = pulse velocity through the material;

ε_m = relative dielectric constant of the material; and

C = pulse velocity through air, which is 1 ft./ns (3×10^8 m/sec), and equivalent to the velocity of light.

When the electromagnetic pulses are directed through a delaminated bridge deck that has been overlaid, as depicted in Figure 3, there will be some reflection from the deteriorated concrete, in addition to the usual reflections at the air-bituminous concrete and bituminous concrete-portland cement concrete interfaces and the reinforcing steel. If the delamination is in an advanced stage, that is, the concrete around a corroded rebar has crumbled, the interface between the sound portland cement concrete and the delamination would likely be more complex, and the resulting reflection thereby more pronounced, than if the distress were in the form of only a crack in the concrete.

Similarly, if the bond between the overlay and the deck is defective, the interface would likely be different from one corresponding to ideal bonding. Theoretically, then, the shape of the composite waveform recorded when electromagnetic pulses are directed through an overlaid deck is influenced by the condition of the deck and, therefore, provides a qualitative picture of the condition of the deck. It must be emphasized that the same argument can be made for bridge decks which do not have overlays, so ground-penetrating radar would likely be applicable to this type of decks also.



SKETCH OF A SINGLE PULSE AND REFLECTIONS AS SEEN BY THE RECEIVER

EXAMPLE OF PROFILE INFORMATION AS DISPLAYED BY THE GRAPHIC RECORDER

Figure 2. Data presentation of ground-penetrating radar.

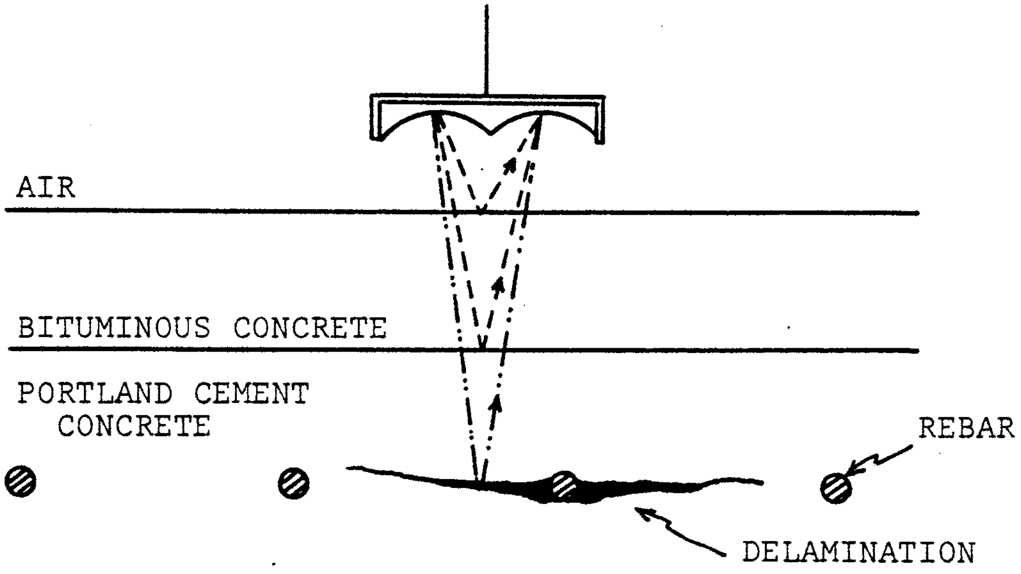


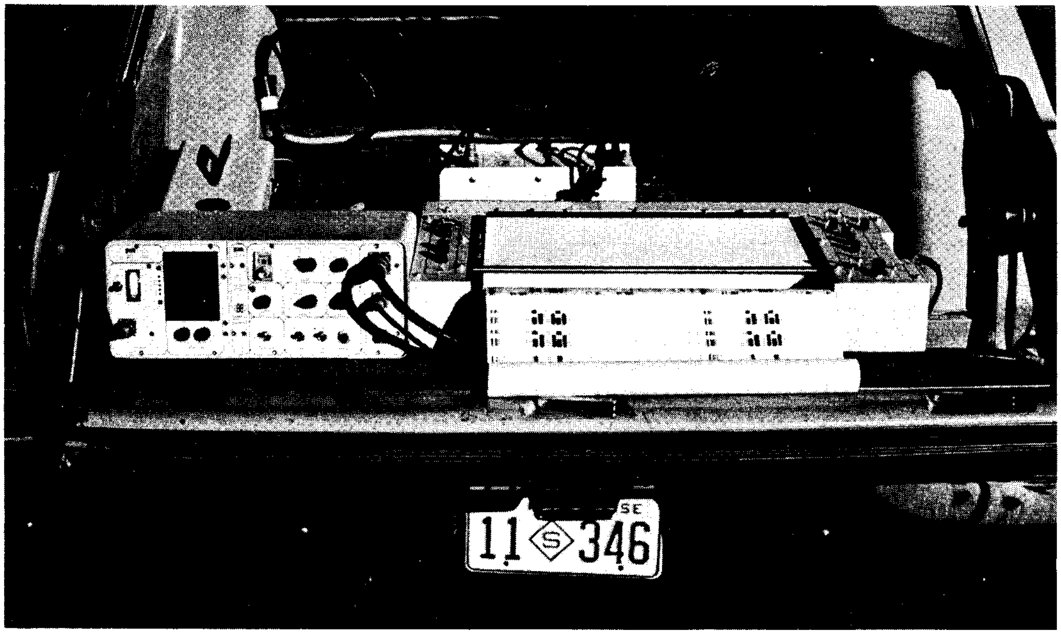
Figure 3. Transmission of radar pulses through a delaminated bridge deck that has been overlaid.

EXPERIMENTAL PROCEDURES

Instrumentation

The pulse radar system used during this investigation was manufactured by Geophysical Survey Systems, Incorporated, of Hudson, New Hampshire. It consists of a model 4400 control unit, an EPC 2208 graphic recorder, a model 02 power distribution unit, and a model 101C transducer. The transducer was selected because it provides the narrowest pulse (approximately 1.1 nanosecond) of all the GSSI transducers and will provide the best resolution of the different pulses reflected from the interfaces in a non-overlaid or overlaid deck.

During field work, the system was carried in the back of a stationwagon, and was laid out as shown in Figure 4. Power was supplied by the 12-volt car battery, with the car engine at idle, through the power distribution unit, which also supplied the 120 VAC needed for the recorder (Figure 5). Before any survey was performed, a model P460 calibrator, which is shown in Figure 6, was connected to the control unit in place of the transducer to provide 10-nanosecond impulses for calibrating the time (or depth) scale on the graphic chart.



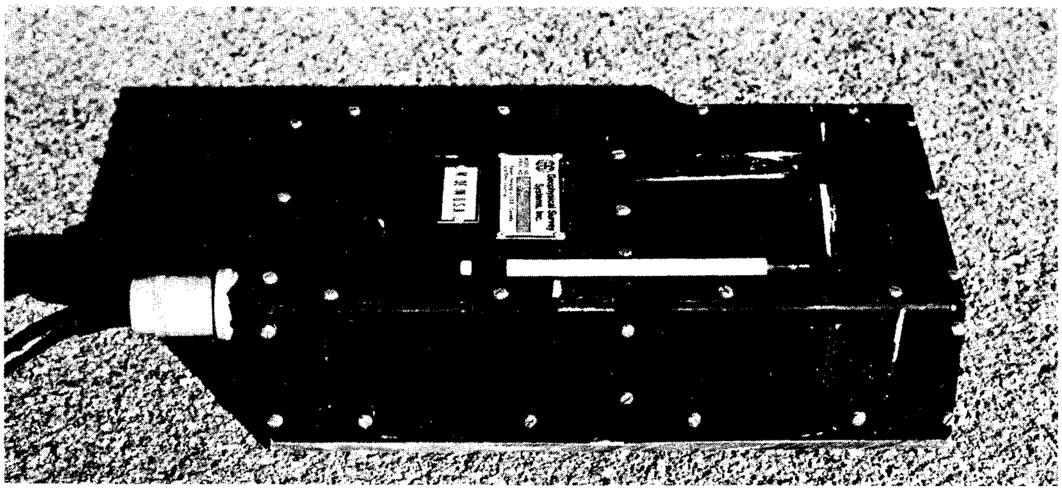


Figure 4. Instrumentation for radar subsurface profiling.

Top: Clockwise from the lower right — the graphic recorder, control unit, and power unit.

Bottom: 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.

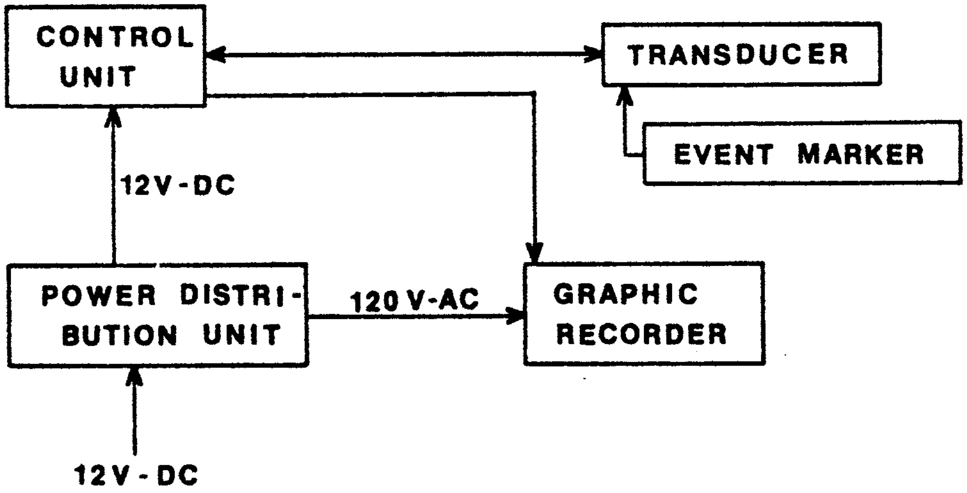


Figure 5. Block diagram of the pulse radar system.

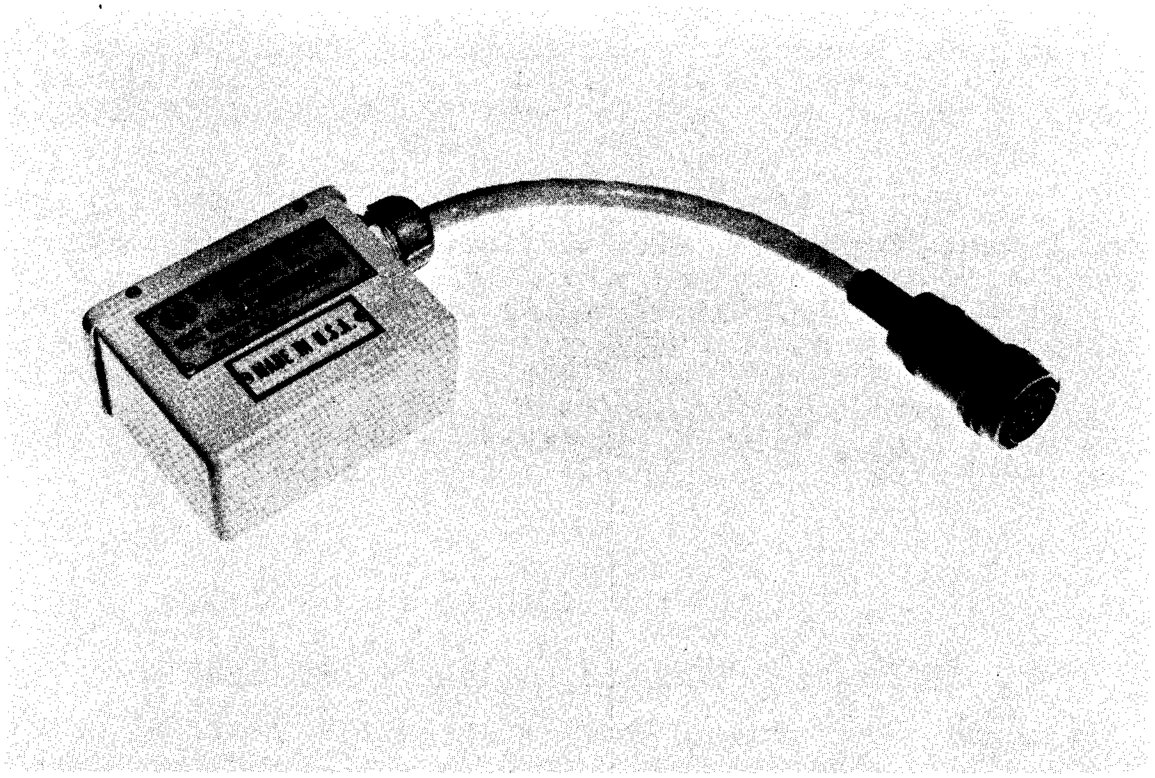


Figure 6. Model P460 calibrator.

Procedure Used in Survey of Bridge Decks

Three overlaid bridge decks were surveyed with the ground-penetrating radar in this investigation. At every 2-ft. (0.6-m) interval across the transverse direction of each deck, a survey (or scan) line was made by manually towing the transducer, which sat above an appropriate dielectric spacer (to be discussed later), over and along the length of the deck, or span, depending on whether the survey was for the entire deck or just selected spans. In addition, each scan line was divided into 2-ft. (0.6-m) segments and properly marked for location references. The typical towing, or scan, speed was estimated to be approximately 20 ft./min. (6.1 m/min).

During each linear scan, whenever the transducer was directly over one of the marked points, which were separated at 2-ft. (0.6-m) intervals, the event marker was activated at the push of a button so that intermittent lines were instantaneously and automatically printed on the graphic chart for location marking. To simplify the interpretation of the radar reflection profiles, only the negative signal peaks were recorded in every scan.

During the scheduled repair of two of these overlaid decks, the delaminated concrete areas were located with the conventional dragging of chains, supplemented with hammering, immediately after the overlays were stripped from the decks.

In addition to these overlaid bridge decks, portions of two existing concrete bridge decks in Virginia and two sizeable old concrete deck slabs, each measuring slightly larger than 6 ft. x 12 ft. (1.8 m x 3.6 m) and belonging to the Federal Highway Administration, were also studied with the ground-penetrating radar. These slabs, which were about 7 in. (17.8 cm) thick, had been carefully saved, for experimentation purposes, during the replacement of a deteriorated deck. Delaminated areas in these decks and slabs were similarly located by chain dragging and hammering.

RESULTS AND DISCUSSION

Non-Overlaid Concrete Slabs and Bridge Decks

In addition to prerequisites such as rapidness and cost-effectiveness, it is also desirable for ground-penetrating radar to be uncomplicated, as far as data interpretation is concerned, for it to gain wide acceptance as a useful inspection technique for bridge decks. Therefore, it was hoped in the beginning of this investigation that the pulse-reflection profile recorded on the graphic chart when the transducer is towed over a delaminated deck would show distinct differences between sound and deteriorated concrete so that the latter could be easily identified. However, since it wasn't known what pulse-reflection profiles corresponding to deteriorated concrete in an overlaid bridge deck would appear like on the chart, it was necessary to observe the profiles for deteriorated non-overlaid concrete decks first. Therefore, as mentioned earlier, two concrete-bridge decks and two deck slabs were also studied, although the primary goal of this investigation was to develop a nondestructive technique for overlaid decks.

Delaminations occur mostly around the top mat of reinforcing steel, which is often less than 2½ in. (6.4 cm) below the surface of the concrete deck. Assuming that the dielectric constant of concrete is approximately 6, as reported elsewhere,(11) the transit time of the radar pulse reflected from a delaminated area at those depths is likely to be less than the 1.1-nanosecond width (or clear time) of the transmitted pulse, according to equation 3. This would result in the reflected pulse being masked by the transmitted pulse, unless a dielectric spacer were inserted between the transducer and the surface of the concrete deck.(11)

Ideally, a spacer should be of a material whose dielectric property is identical to that of concrete. Since dry and well-compacted sand was reported to have a dielectric constant close to that of concrete,(12) it was selected for use in this investigation. (Subsequent measurements made on five 8-in. (20-cm) thick reinforced concrete slabs that had been treated to simulate the typical salting of bridge decks during winter yielded dielectric constants ranging from 9 to 13, and having an average of 12. These results indicate that winter salting can significantly change the ionic composition, and therefore the electrical properties, of typical salted concrete decks and result in higher dielectric constants than those previously reported for unsalted concrete slabs. As a consequence dry sand may not be the most suitable dielectric spacer for surveys of concrete decks as expected earlier. A similarly salted concrete slab approximately 2-in. (5-cm) thick may be preferable.)

In using sand as a dielectric spacer, two wooden boxes were constructed from 1/2-in. (1.3-cm) finish wood in such dimensions that dry sand could be compacted to the desired thicknesses (4 and 8 in. [10.2 and 20.3 cm] were selected)while leaving enough space on top to securely accommodate the transducer. A sketch of the setup with the smaller sand box is shown in Figure 7. These setups were utilized in surveying the two non-overlaid concrete bridge decks and two deck slabs mentioned earlier.

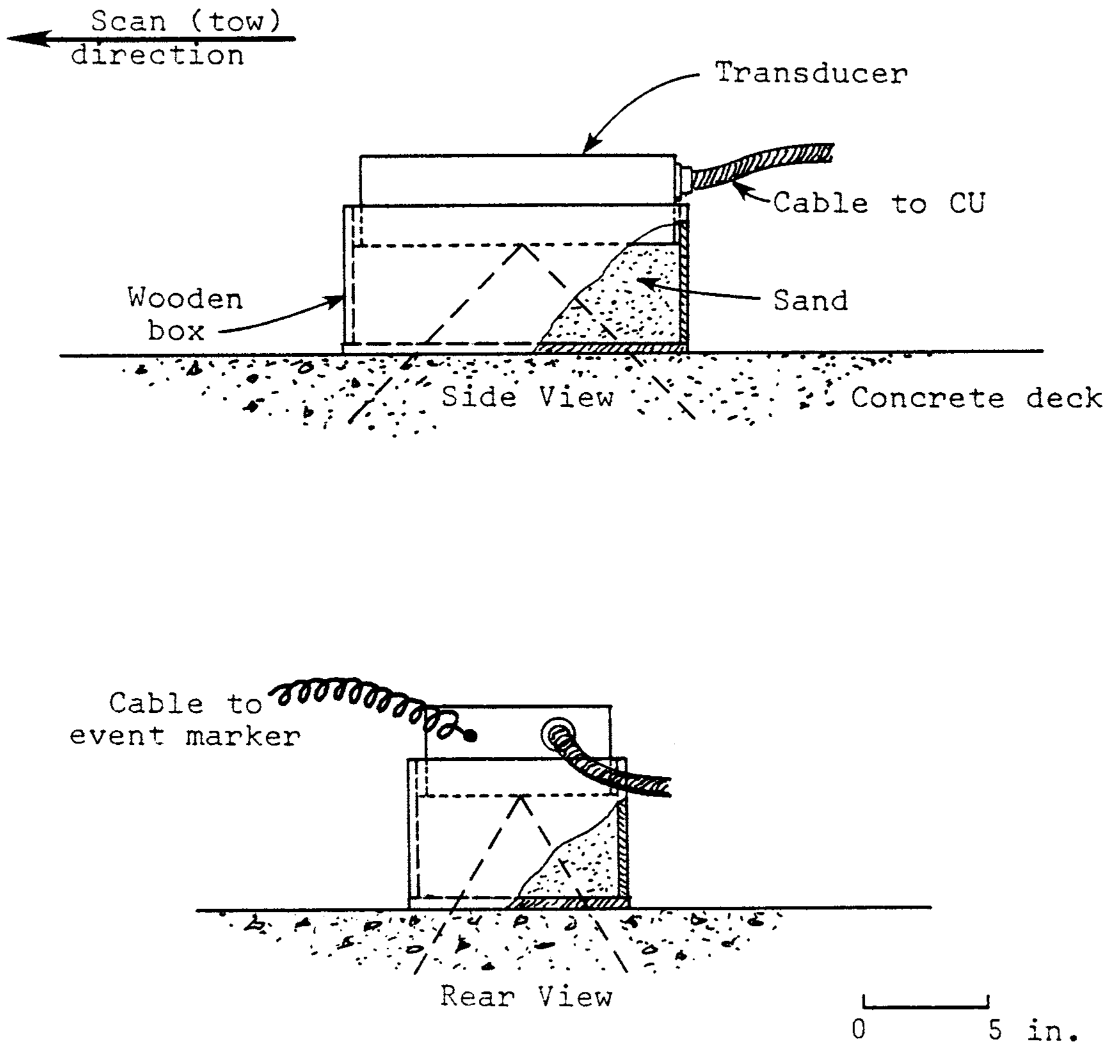


Figure 7. Sand box used as a dielectric spacer for concrete deck (1.0 in. = 2.54 cm).

Concrete Deck Slabs

Figure 8 shows the condition of the FHWA concrete deck slabs (labelled GL-2 and G-2) as determined by visual inspection and sounding with chains and a hammer. The vertical bands of a very thin coat of an asphalt-sand mix on these slabs appeared to be applied for improving the adhesion of traffic paint to the original deck, and means that the lengths of these slabs are along the transverse direction of the deck. This deduction is further supported by scaling and exposed aggregate typical of traffic wear on both sides of each band of the asphalt-sand mix. It should be mentioned that all delaminated areas in these slabs appeared along wheel paths, as evidenced by the scaling and exposed aggregates.

Figures 9 through 11 show three sets of radar reflection profiles corresponding to the several line scans made at 1-ft. (0.3-m) intervals on each of the slabs using the two sand-dielectric spacers separately.

As discussed earlier, the shape of the radar reflection profiles, and/or any irregularities therein, theoretically should provide qualitative pictures of a deck. For example, Figure 9 shows five reflection profiles representing the five line scans made on Slab GL-2 using the 8-in. (20.3-cm) spacer. (To determine which reflection bands come from the top mat of reinforcing bars, assume that salted concrete has an average relative dielectric constant of 12 and the average depth of concrete cover of these bars is 2.5 in. (6.25 cm). Then use eq. 3 to calculate the transit time for this top layer of concrete. Since an 8-in. (20.3-cm) sand spacer was used, one should also calculate the transit time corresponding to this material by assuming a relative dielectric constant of 6. Combined the two resulting transit times give a total transit time of approximately 5 nanoseconds, which in the profiles shown in Figure 9 corresponds to the blip type signals that arise from the small cross section of rebars. In some profiles presented later these blip type signals are even more pronounced so that one can tell right off which reflections came from the top mat of rebars.)

Looking first at scan line 1, one can see a distinctive depression from the 8-to the 11-ft. (2.5- to 3.4-m) mark and at the depth of the top mat of reinforcing bars. This depression corresponds to a nearby delaminated area that was located by conventional sounding as shown in the top portion of Figure 8. In scan line 2, which was 1 ft. (30.5 cm) below the preceding scan, the same feature appeared from about the 8-to the 11-ft. (2.5- to 3.4-m) marks, where the transducer went directly over the delamination. This feature was similarly observed in the remaining scans, except in scan line 5, where it was practically not discernible. The slight rugged feature to the left of the depression and at about the 0.5- to 3.5-ft. (0.2- to 1.1-m) area cannot be fully accounted for by the asphalt-sand band. It is probable that there was incipient deterioration along both sides of the asphalt-sand band, since those areas were wheel paths and, as mentioned earlier, all the delaminated areas in these slabs were located in the wheel paths.

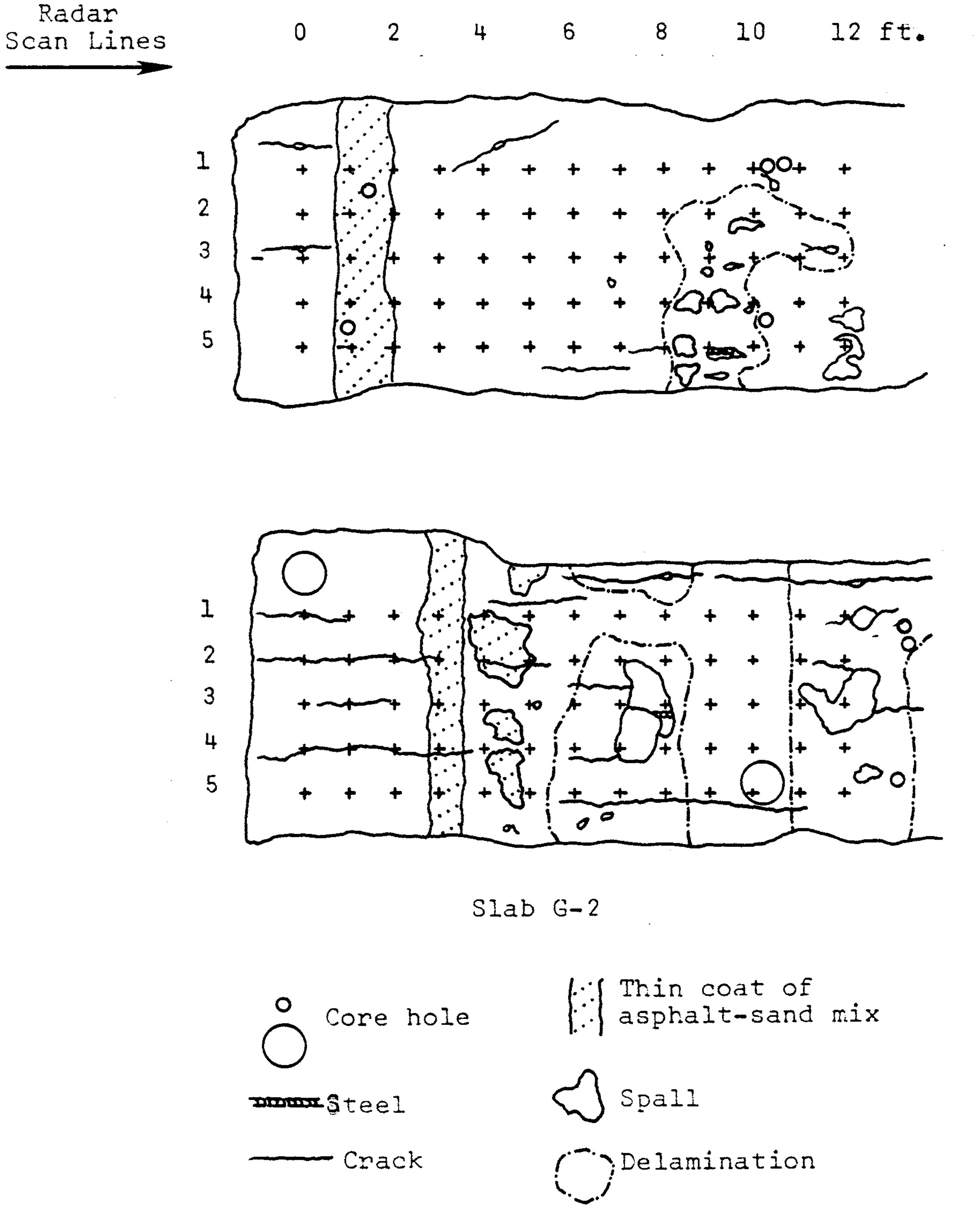


Figure 8. Condition of the two concrete deck slabs.

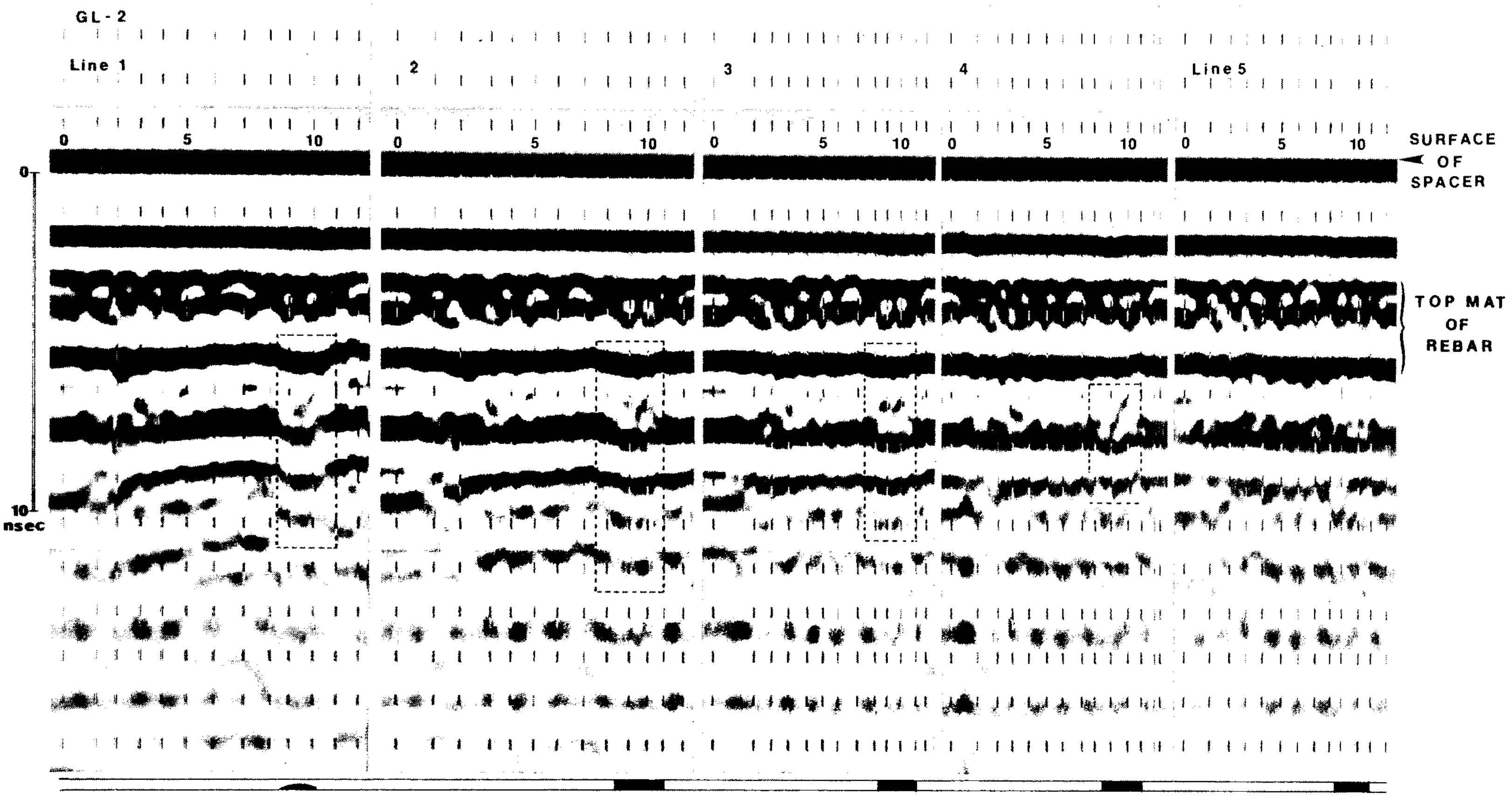


Figure 9. Radar reflection profiles for slab GL-2 obtained with 8-in. (20.3-cm) sand dielectric spacer. (Shaded areas in bottom strip correspond to delamination located by conventional sounding directly under the path of the transducer. Such strips are subjoined to recorded reflection profiles for ease of comparison.)

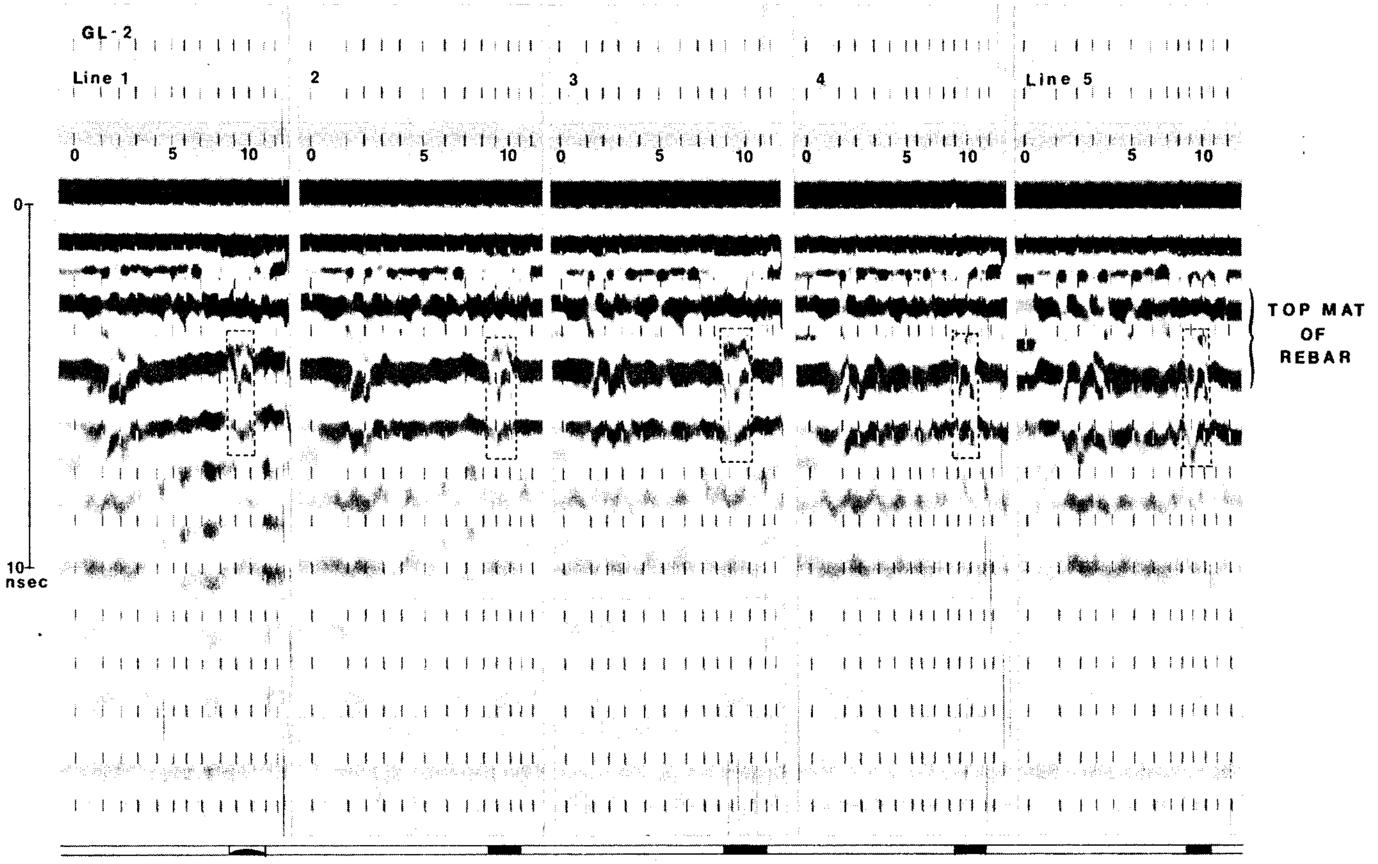


Figure 10. Radar reflection profiles for slab GL-2 obtained with 4-in. (10.2-cm) spacer. (Shaded areas in the bottom strip correspond to delamination located by conventional sounding.)

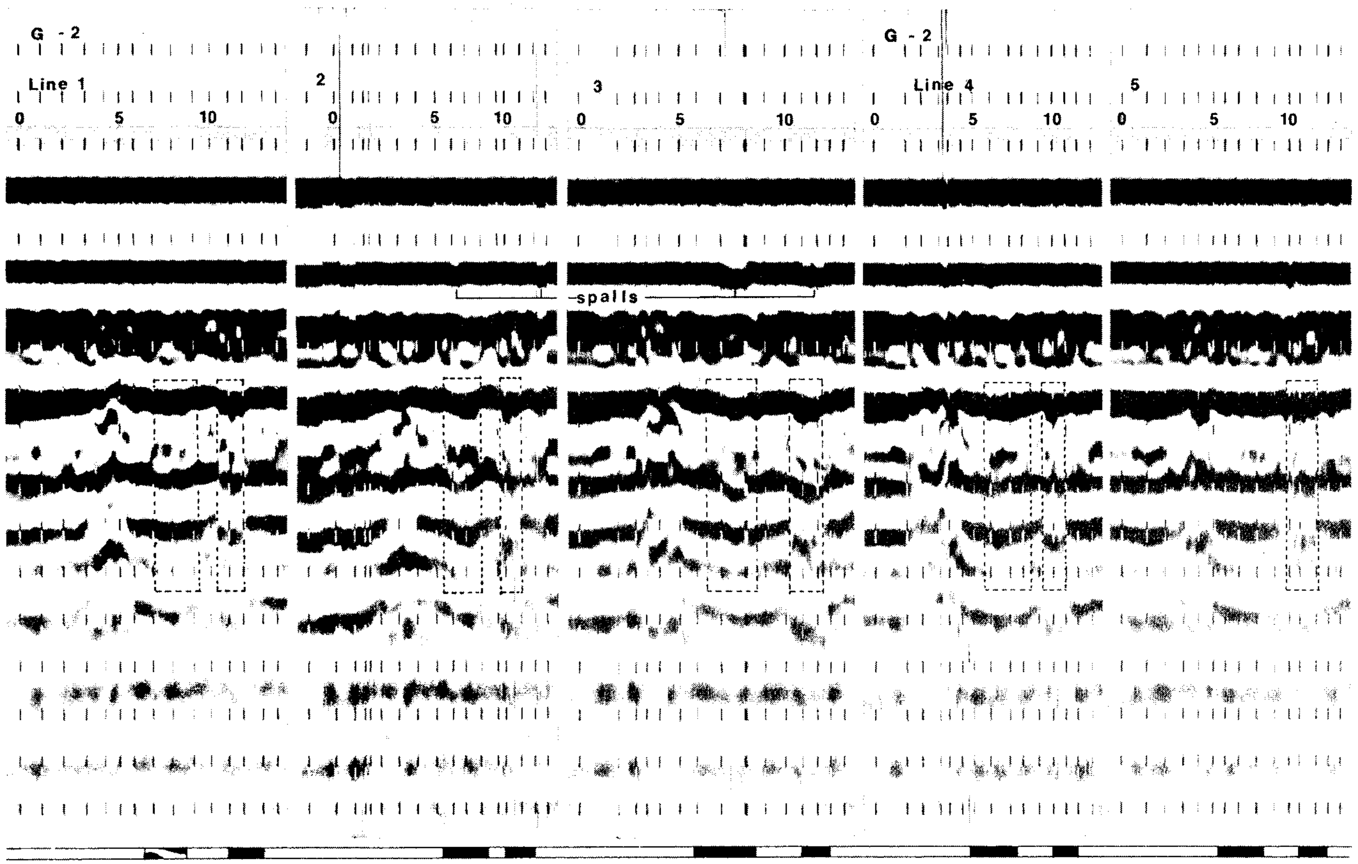


Figure 11. Radar reflection profiles for slab G-2 obtained with 8-in. (20.3-cm) sand dielectric spacer.

Figure 10 shows the set of radar reflection profiles obtained when the same deck slabs were similarly scanned using the smaller dielectric spacer. Here the signature for the same delaminated area, which extends from above the 8- to 11-ft. (2.5- to 3.4-m) marks, appeared as doublets instead of the depressions shown in Figure 9. Closer examination of the shape of the depressions, particularly the one in Figure 9 and scan line 3, which shows more detail than the rest, revealed a slight resemblance between the depression and doublet, so that one may likely be a variant of the other.

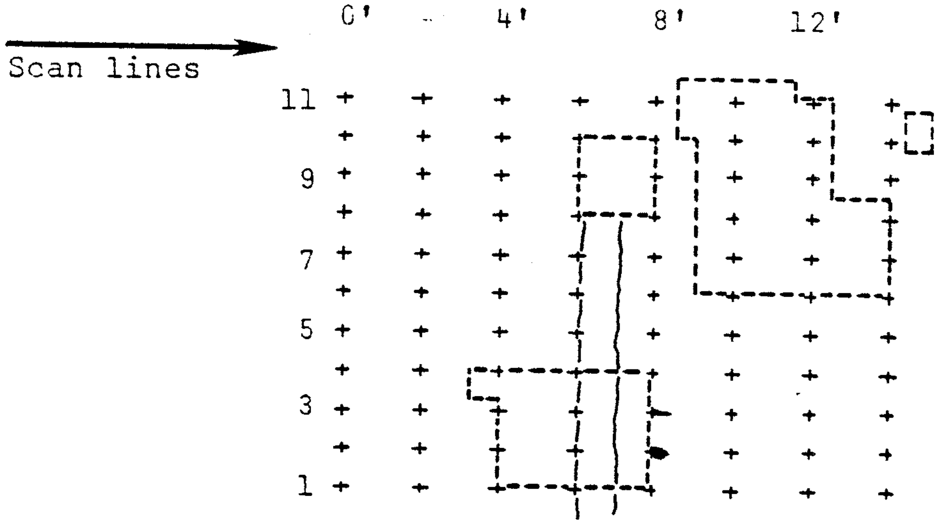
Although the doublet is weak in scan line 5, it is relatively easy to recognize in contrast to the same scan in Figure 9, where the known delamination is hardly manifested in the reflection profile. Again, a rugged feature of uncertain origin appeared between the general area of the 1- to 4-ft. (0.3- to 1.2-m) marks as shown in Figure 9.

Similar scanning of the second slab, G-2, with the 8-in. (20.3 cm) dielectric spacer yielded the profiles shown in Figure 11. These feature the same type of depressions, which were determined in the above discussion of Figure 9 to be a typical signature for concrete delaminations. Appearing at the general vicinities of the 6- to 9-ft. (1.8- to 2.7-m) marks and 11- to 13-ft. (3.3- to 4.0-m) marks, these depressions coincided with the two large delaminated areas located by conventional sounding and shown in Figure 8. Notice that spalled areas, those on the paths (scan lines) of the transducer and as small as 0.5 ft. (15.2-cm) wide, showed up clearly on the reflection profiles. This slab was not tested with the smaller dielectric spacer.

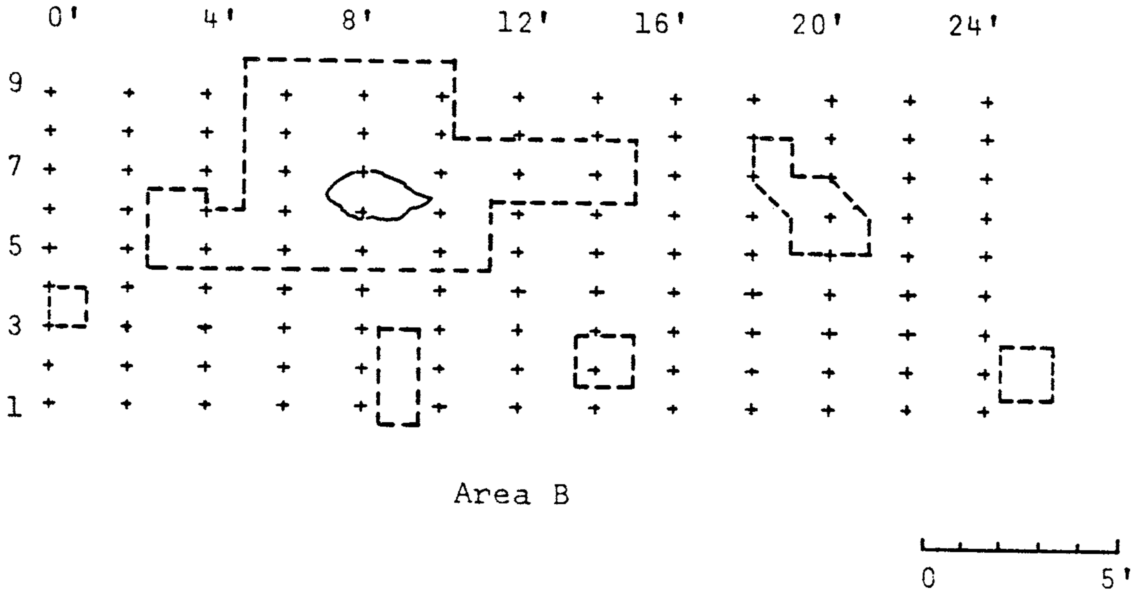
Concrete Bridge Decks

The first concrete deck tested had delaminations in less than 10% of its entire three-span deck area as determined by conventional sounding. Two test areas were selected from two spans to include about 50% of the delaminations. The delaminations in each of the test areas are shown in Figure 12, which also shows the layout of the horizontal radar scan lines 1-11 and 1-9 for test areas A and B, respectively. As is shown, these scan lines were separated 1 ft. (0.3 m) apart.

Figure 12 shows that test area A contained two large delaminated areas and a relatively smaller one. The large delaminated area located between the 4- and 8-ft. (1.2 to 2.4-m) marks was detected by the transducer as it went over the area with the 4-in. (10.2-cm) dielectric spacer on scan lines 1 through 4 as shown in Figure 13. The results obtained with the larger dielectric spacers were practically identical to those obtained with the 4-in. (10.2 cm) spacers, and, therefore, only those obtained with the latter are presented here. This delamination was manifested in the reflection profiles as a customary depression.



Area A



Area B

Figure 12. Test areas in concrete deck no. 1.

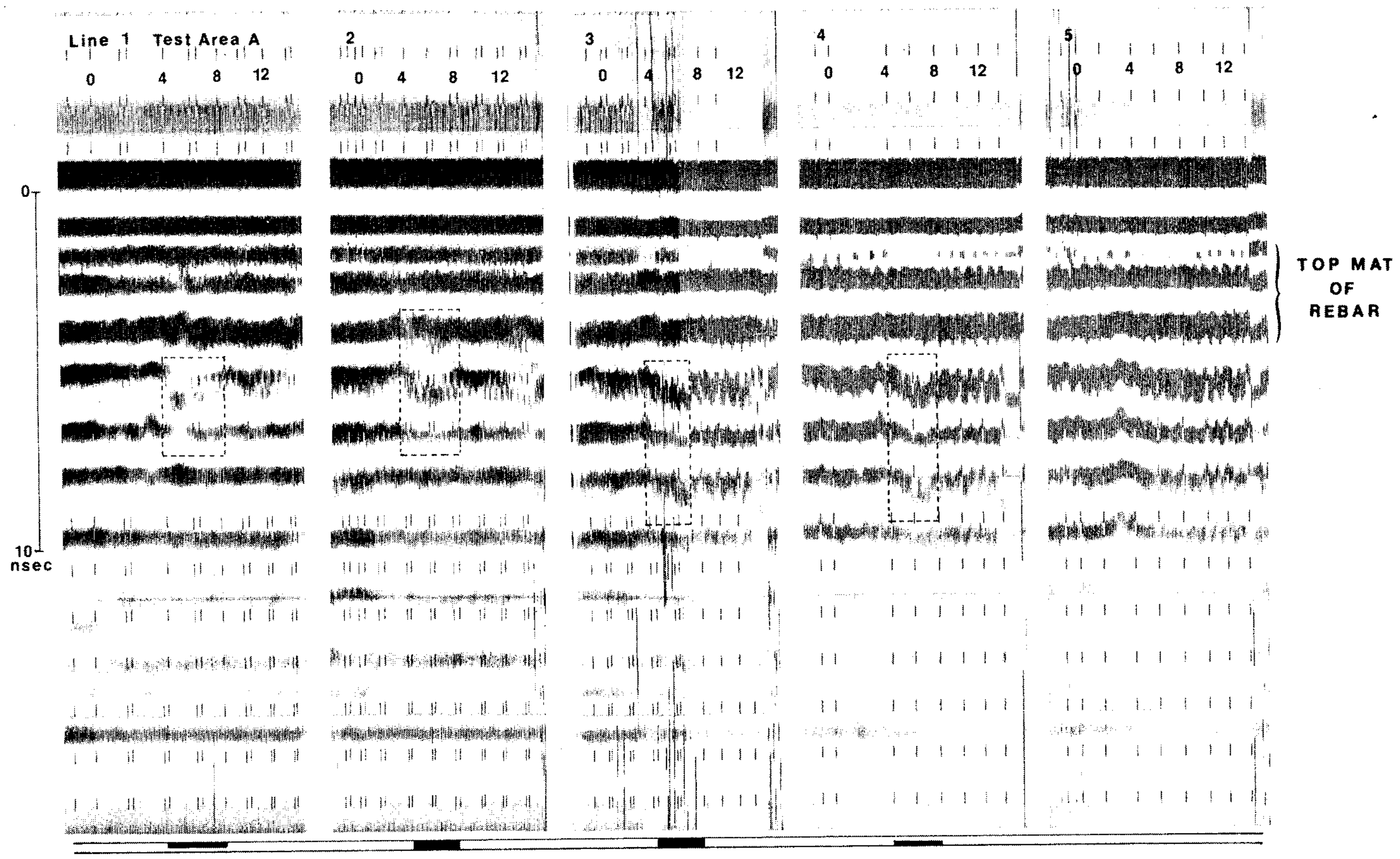


Figure 13. Radar reflection profiles for test area A in concrete deck no. 1.

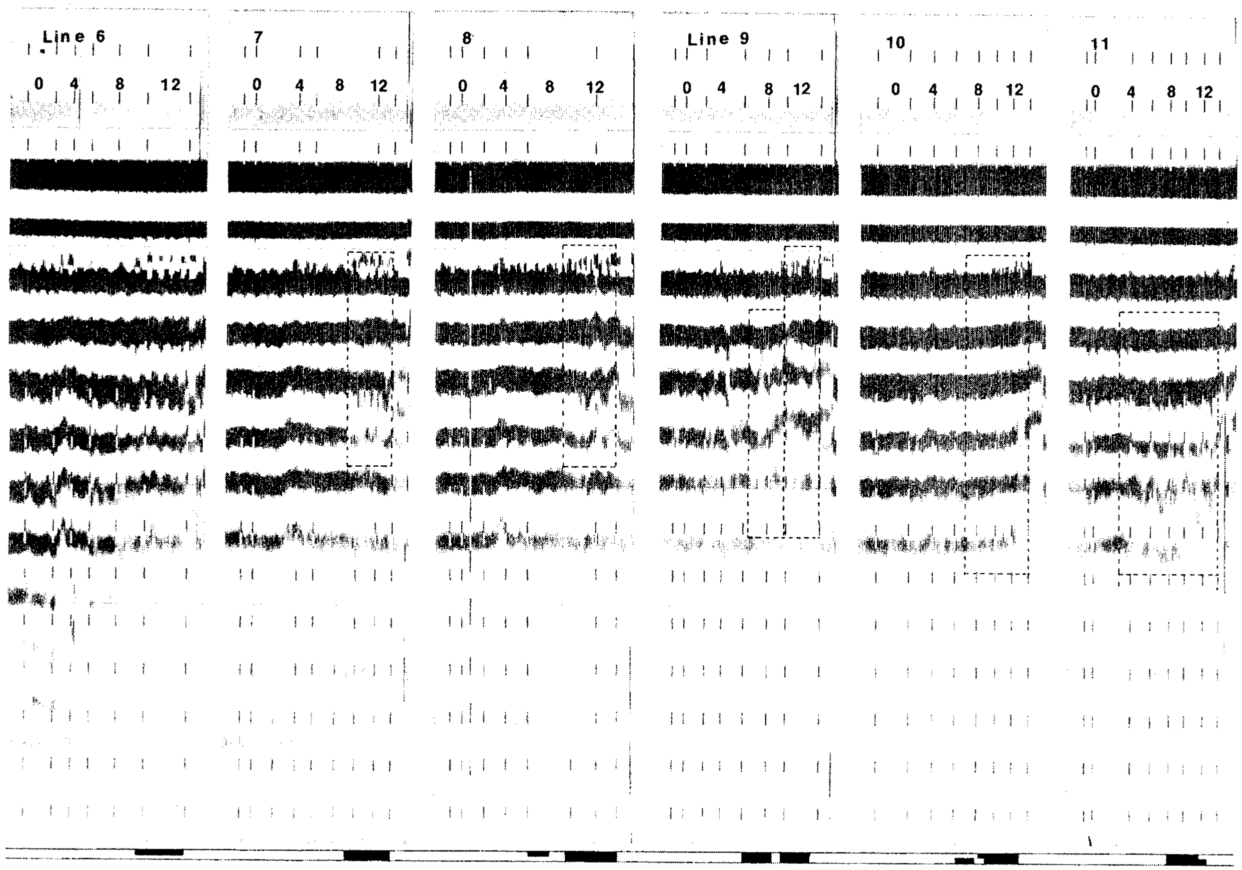


Figure 13. Continued.

The transducer began to "see" the remaining large delamination in the upper-right quadrant of the test area in scan line 7. The neighboring smaller delamination wasn't noticed until scan line 9, and even then it wasn't distinguished from the larger one. However, it is probable that the entire quadrant was delaminated as indicated in scan line 11. Furthermore, for practical purposes delineating the two neighboring delaminations may not be important.

Notice that in the reflection profile for scan line 10 the portion from the 6- to 14-ft. (0.9 to 4.3-m) marks that corresponds to the delaminations in the upper-right quadrant appeared noticeably different from the rest of the profile. It is uncertain how radar pulse reflections from delaminations in concrete can give rise to this type of ascending signature. Such signatures have been observed in a portion of an overlaid bridge deck suspected by bridge maintenance engineers to be in need of repair.

As shown in Figure 12, test area B had one very large and several relatively small delaminations that were located by conventional sounding. Just beyond the lower right boundary of this test area was another small delamination. An examination of the reflection profiles for scan lines1-4, which are presented in Figure 14, indicated that the transducer didn't pick up the three small delaminations in the lower half of the test area. However, it did see the small delaminations just outside the lower right corner during the end of scan line 2. It has not been determined yet what caused this discrepancy or, more appropriately, inconsistency. Perhaps, the smallest delamination that the technique can pick up with the present experimental setup is one about 1 ft. (0.3 m) across.

The large delaminated area in the upper half of the test area was easily picked up by the transducer, as manifested in the customary depressions in scan lines6-9 in Figure 14. It is interesting to note that the delaminations located along scan line 5 appeared blurred in the reflection profile. Lastly, the smaller delamination located between the 18- and 20-ft. (5.5 and 6.1-m) marks (Figure 12) showed up faintly in the profiles of scan lines 7 and 9.

A different experiment was performed on the deck designated concrete deck no. 2. In this experiment, a few straight lines (or scan lines) connecting sounding-located delaminations of various sizes were drawn on the deck. Then for each line, a forward scan was made with the transducer atop the 4-in. (10.2-cm) dielectric spacer, then this scan was reversed by tracing the path of the transducer back to the starting point.

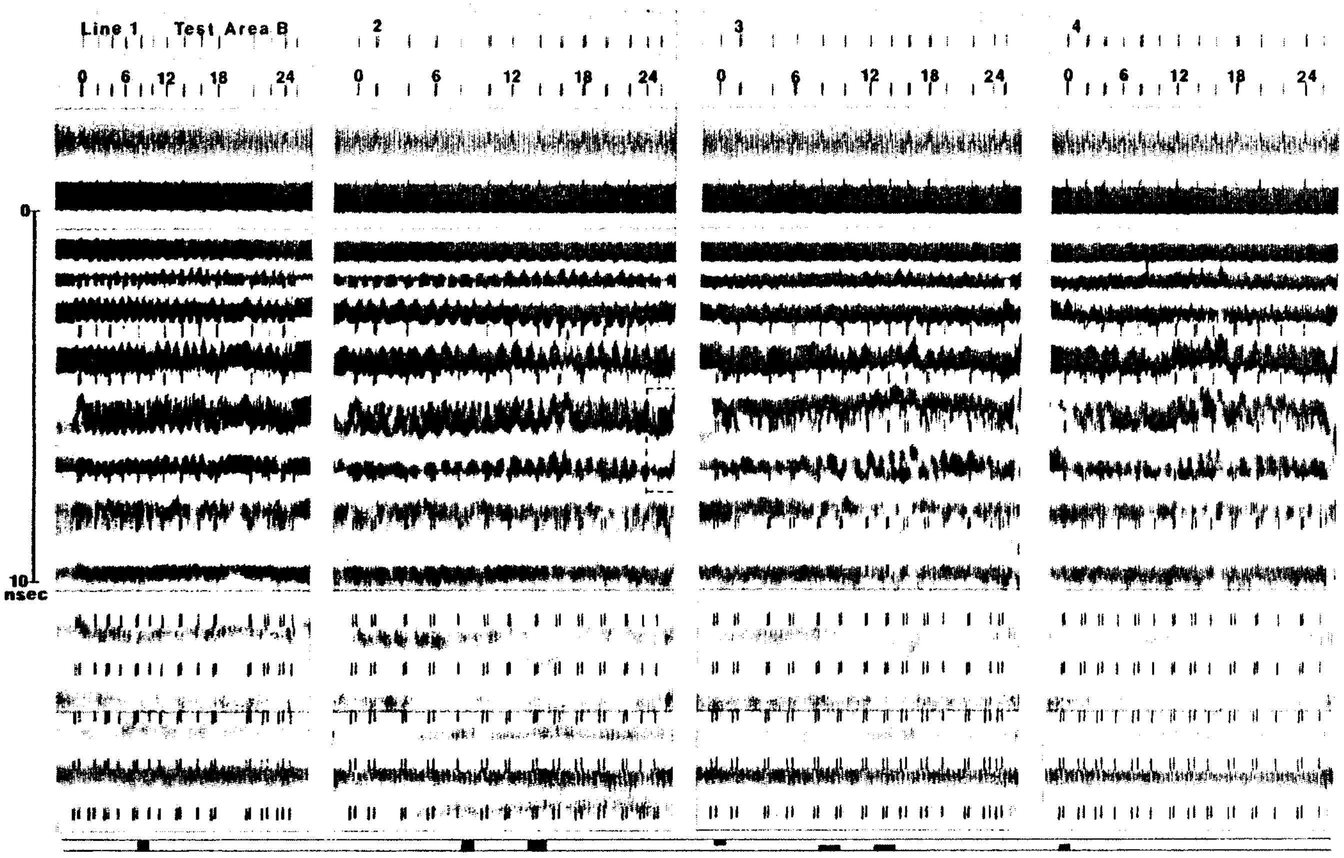


Figure 14. Radar reflection profiles for test area B in concrete deck no. 1.

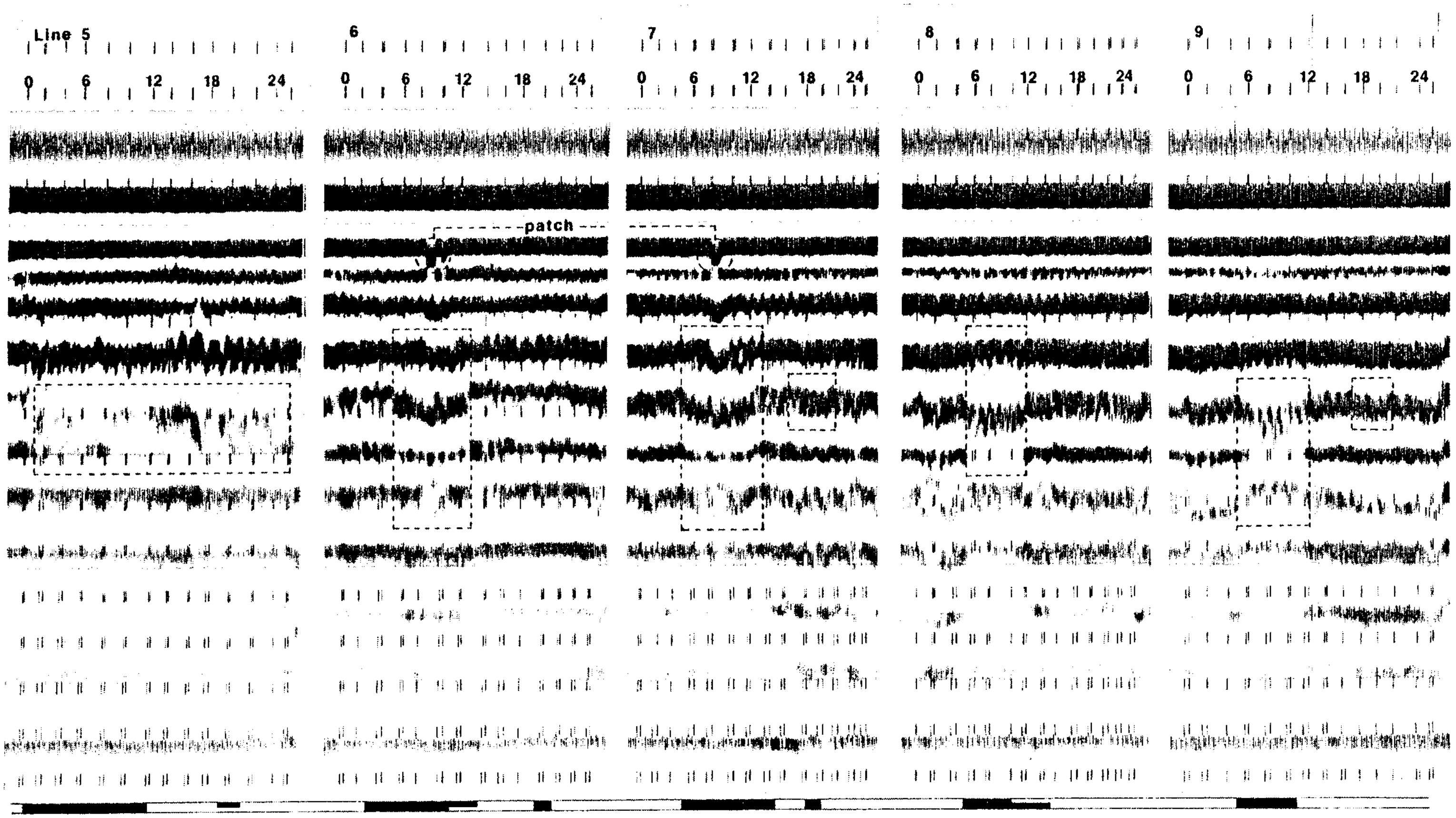


Figure 14. Continued.

Figure 15 shows a typical example of the results. This particular line connected three delaminated areas designated del. #1, #2, and #3, which were approximately 1.5, 3.0, and 1.0 ft. (0.5, 0.9 and 0.3 m) across, respectively. As is evident, the reflection profile for the reversed scan was practically a mirror image of that for the forward scan, except for fluctuations in the rate at which the transducer was towed. This indicates that the technique is quite reproducible.

Compared to the results obtained for the first concrete deck (Figures 13 and 14) and the two FHWA concrete deck slabs (Figures 9-11), the delaminations in this deck were picked up very distinctively, as shown by the strong depression features which correspond to reflections at the depth of the top mat of rebars in Figure 15.

In summary, the results for the concrete slabs and decks generally showed that there are sufficient observable differences between radar pulse reflections from sound and those from delaminated concrete to allow identifying delaminations. The signatures of delaminations are usually in the shape of a depression with occasional doublets, "ascending", and "blurred" reflections.

The transducer didn't have difficulty in picking up relatively large delaminations; however, it was less consistent for delaminations about 1 ft. (0.3 m) across.

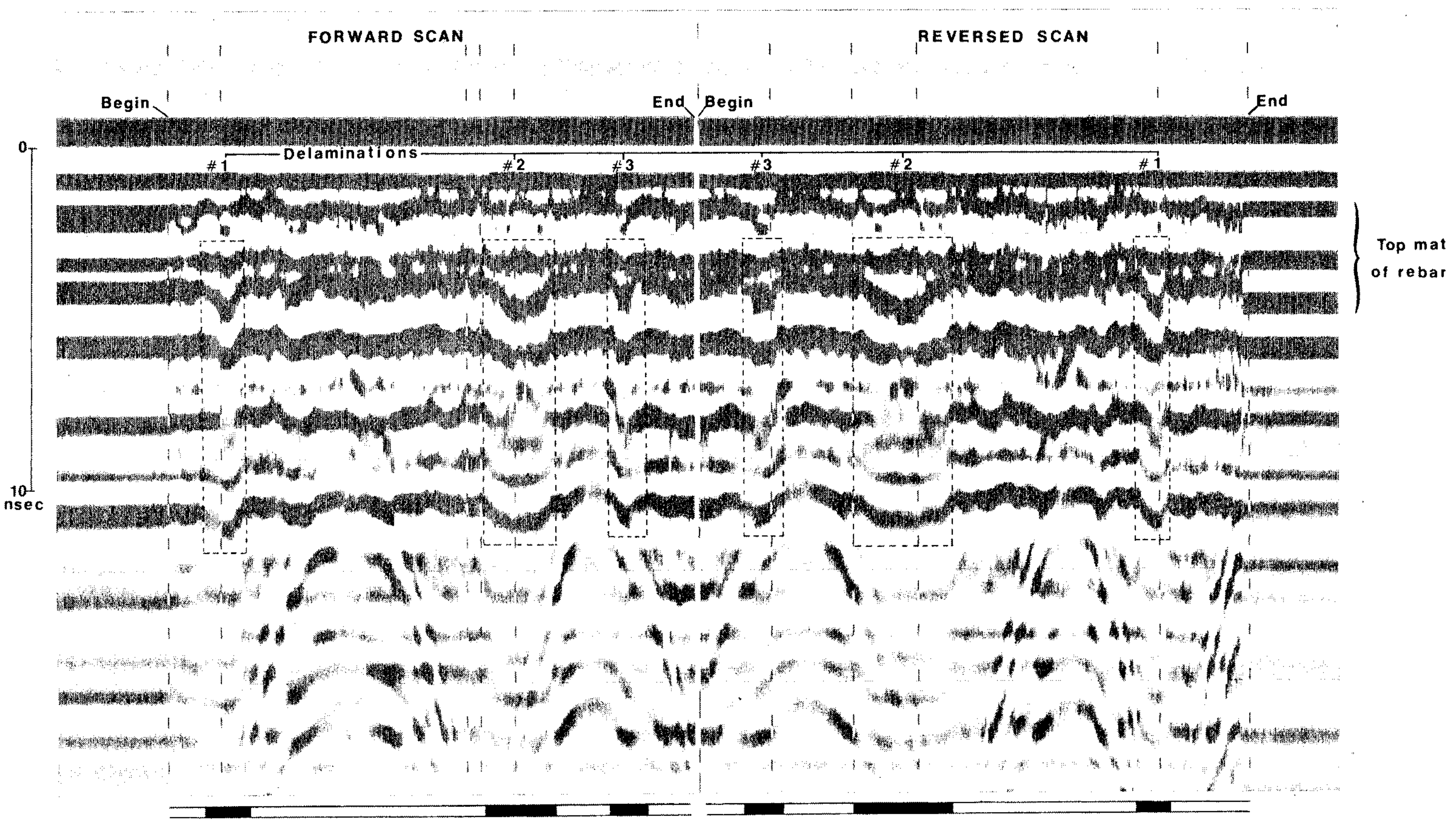


Figure 15. Forward and reversed scans on concrete deck no. 2.

Overlaid Concrete Bridge Decks

Three overlaid concrete decks were tested with the ground-penetrating radar. For the first two, subsequent surveys by conventional sounding were conducted immediately after the overlays were removed for the deck repairs. The third deck is scheduled for repair during the 1982 construction season, which is beyond the reporting date of this study.

A block made of S-5 bituminous concrete and measuring approximately 8.5 in. wide x 14.0 in. long and 10.5 in. high (21.6 x 35.6 x 26.7 cm) was used as a dielectric spacer in conjunction with the radar system for all three decks. On the third deck, an asphalt block only 2.0 in. (5.0 cm) high was also used for comparison.

Overlaid Deck No. 1

Two spans were randomly selected from this deck and a grid system was laid out on half of each span. As illustrated in Figure 16, each grid consisted of several longitudinal scan lines 2 ft. (0.61 m) apart. Figure 17 shows two of the several radar reflection profiles recorded for span 1 when the transducer, which was sitting atop the large asphalt block, was towed over these lines. These profiles show that reflections from known delaminations also appeared in the shape of depressions, which by now constitute a familiar signature of delaminations.

In an actual application of this radar technique, the user would go through these profiles and search out signature(s) to identify the suspected delaminations under the overlay. Areas in span 1 suspected to be delaminated from the application of this approach, as illustrated at the top of Figure 16, were verified by conventional sounding. This process also indicated that the radar also gave positive results in several locations not judged to be delaminated by sounding, although in all these locations there were cracks in the overlay. Since the width of some of these unmatched depressions were more than what the cracks could account for, one would tend to believe that the radar detected some anomaly in the concrete not revealed by sounding.

Some features of Figure 17 are worth mentioning. The relatively tiny and sharp peaks, or spikes, at the level of the top mat and regularly spaced at approximately 6 in. (15.2 cm) apart are reflections from the rebars. This feature provides a quick determination of which band in a reflection profile corresponds to reflections from the level of the top mat, where delaminated concrete is located, without the need for the mathematical relationships between the dielectric constant and transit time as discussed previously.

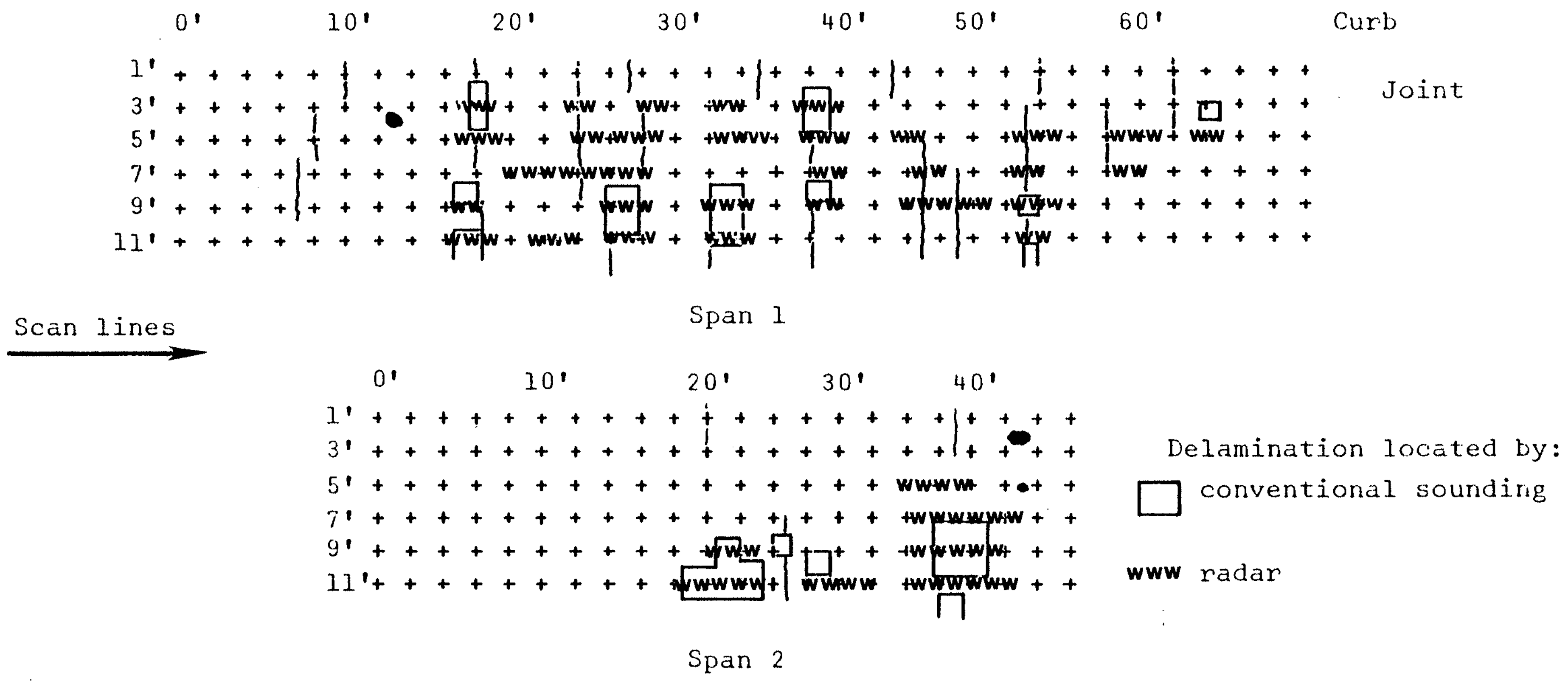


Figure 16. Test areas for overlaid deck no. 1.

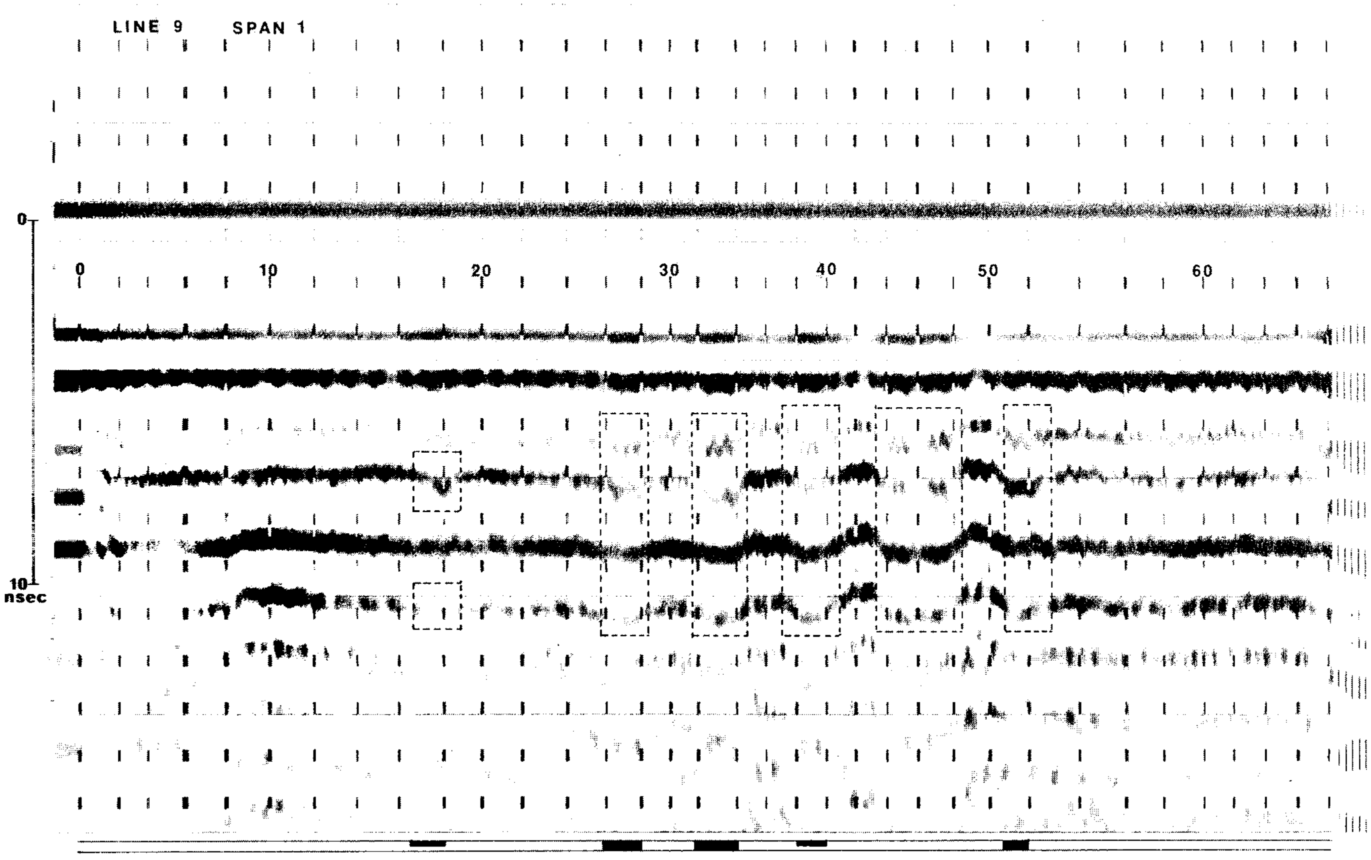


Figure 17. Radar reflection profiles for the test area in span 1 of overlaid deck no. 1.

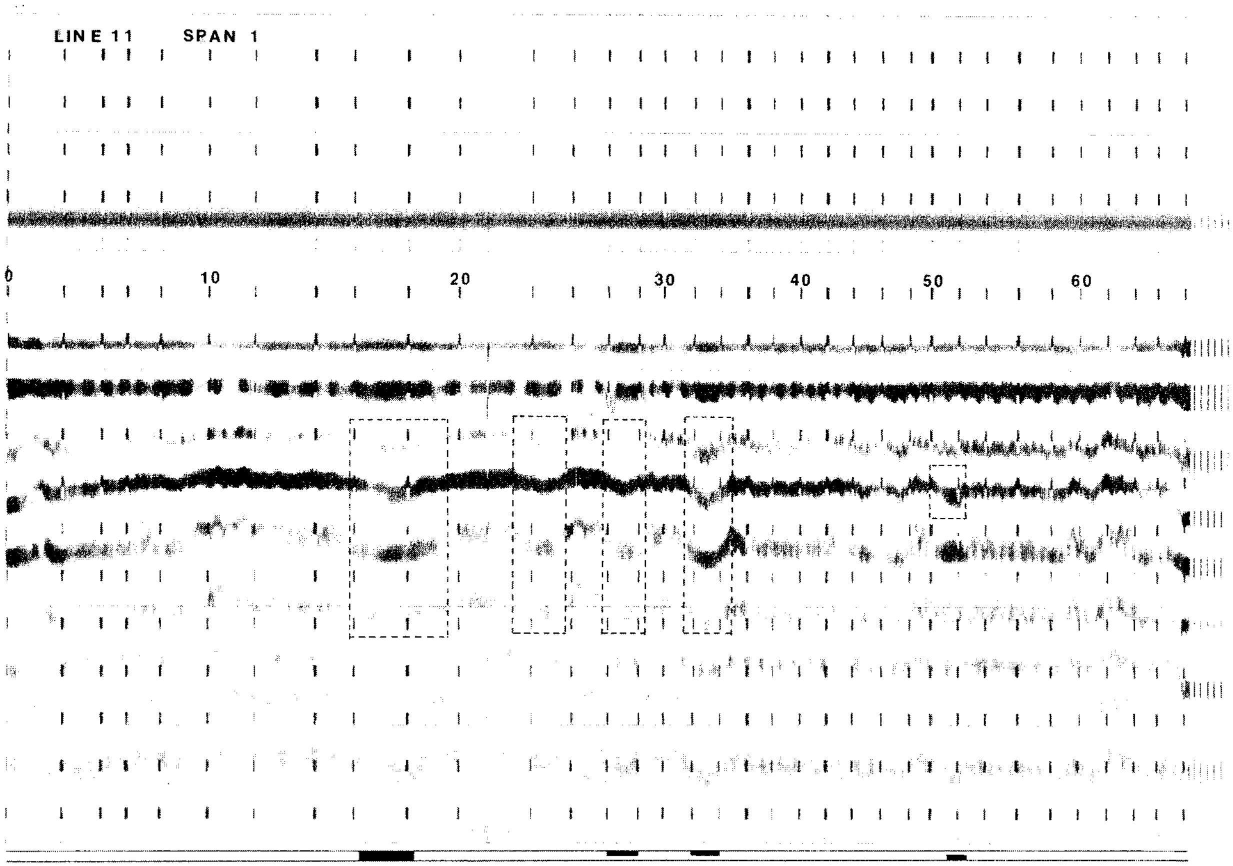


Figure 17. Continued.

Figure 18 shows some of the reflection profiles recorded for the test area in span 2. Similar interpretations of those profiles and comparisons of the resulting suspected delaminations with those located by sounding, as illustrated in the bottom of Figure 16, yielded favorable agreement between the two procedures.

Overlaid Deck No. 2

The second overlaid deck was an arched deck approximately 150 ft. (45.7 m) long and consisting of two 22-ft. (6.8-m) continuous slab spans, a 62-ft. (19.1-m) jointed arch span, and another two 22-ft. (6.8-m) continuous slab spans. A test area approximately 18 ft. x 150 ft. (5.5 m x 45.7 m) was mapped out as shown in Figure 19, which also shows the locations of the cracks in the overlay and the delaminations located by sounding and radar.

Figure 20 shows four of the ten recorded radar reflection profiles for the ten longitudinal scans made on the test area. It is not difficult to infer from a quick examination of these profiles, specially that for scan line 8, that the deck is longitudinally arched, as manifested by the distinctive shape of an arch assumed by the reflection band at the overlay/concrete interface, which is immediately above the top mat of rebars.

The arch in the profiles also implicitly indicated that the thickness of the overlay on the bridge deck can be nondestructively measured by the ground-penetrating radar, as was recently reported by Rosetta.(10) To illustrate this point, consider the reflection profile for scan line 8. Starting from the 0 mark, measure the vertical distance from the bottom of the first band (the transmitted pulse) to the respective point on the arch drawn across the profile at the level of the top mat of rebars. Using the time scale beside the graph, convert this distance into the transit time (in nanoseconds) it took the pulse to travel through the overlay and back. Repeat this at, say, every 10-ft. (3.1-m) interval through the 150-ft. (46.2-m) mark. Then plot the resulting transit times with the actual total thickness of the overlays (Table 1) accumulated through the years on the deck as measured when certain traffic lanes were closed for deck repair. (In an actual application of this approach, the "ground truth" calibration can be achieved by using a steel punch to measure the overlay thicknesses at various points on a deck.) The resulting plot, Figure 21, shows a good linear correlation between the total thickness of the overlay and the radar pulse transit time. It is interesting to note the total thickness of the overlays, approximately 14 in. (0.36 m) at some points, accumulated on this deck. The capability of the radar to nondestructively measure the overlay thickness can be very useful, as in the case of this particular deck. When the contract for repair was being let, difficulty was encountered in estimating the cost for removing the overlay since there was no procedure for determining, before the fact, how much material would be involved.

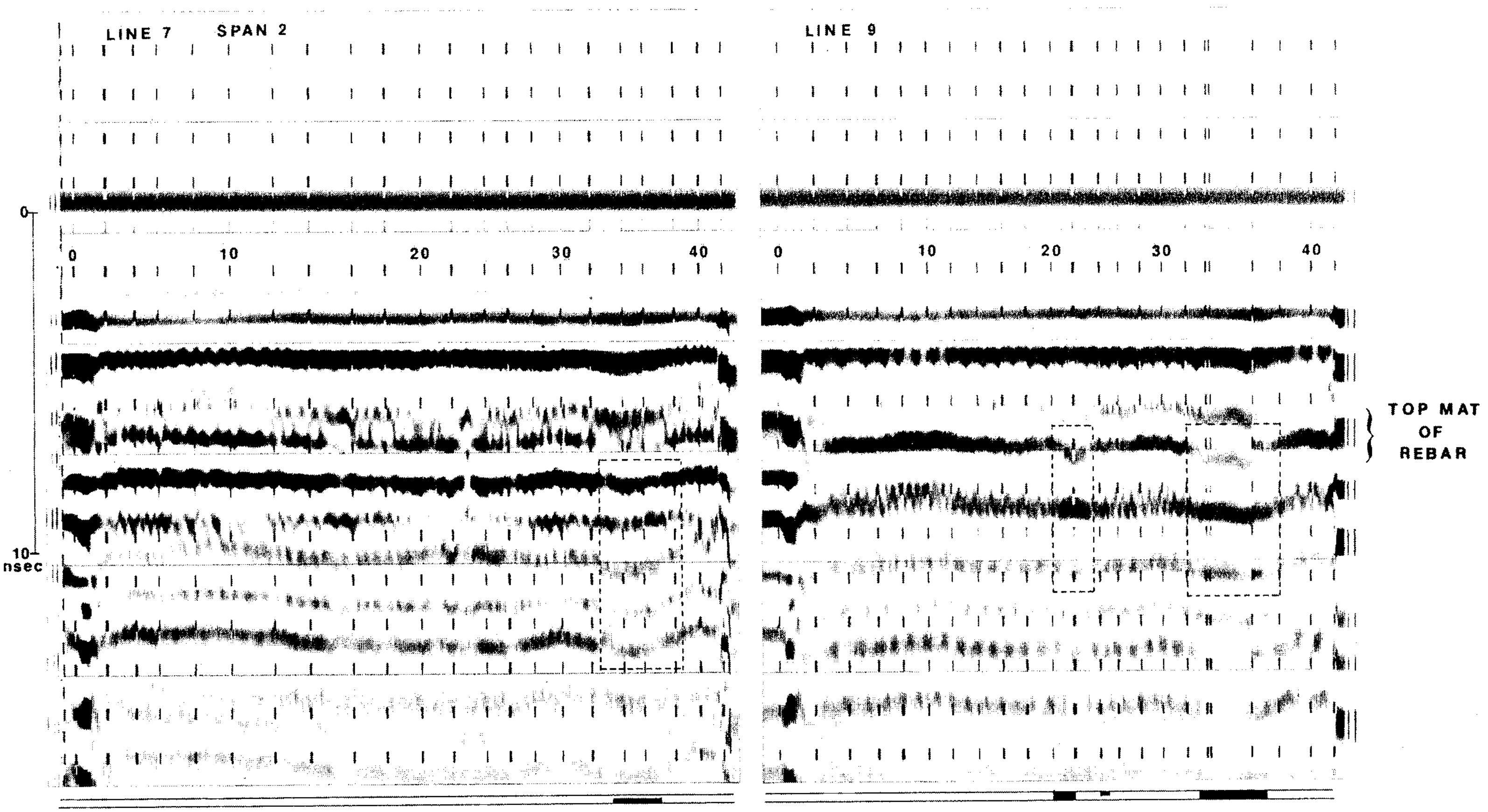


Figure 18. Radar reflection profiles for the test area in span 2 of overlaid deck no. 1.

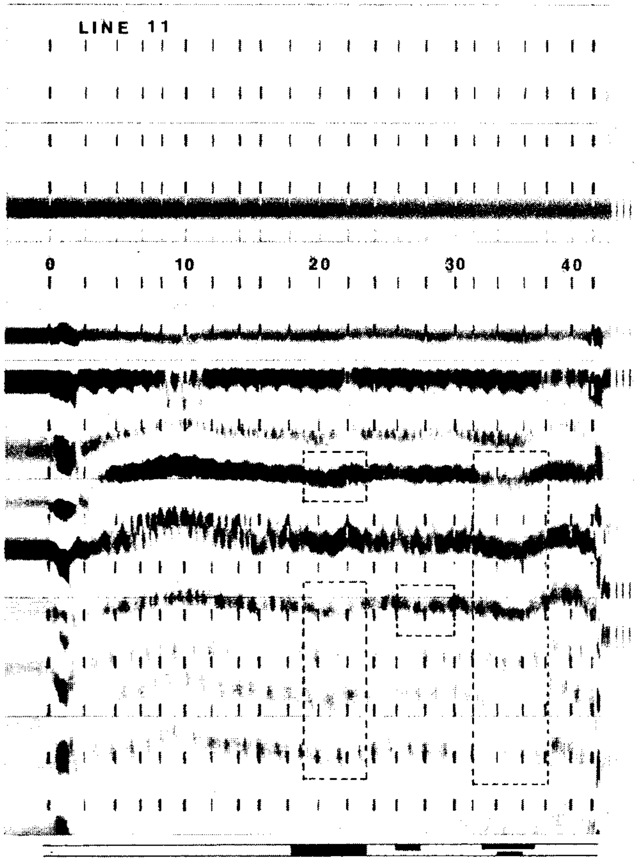


Figure 18. Continued.

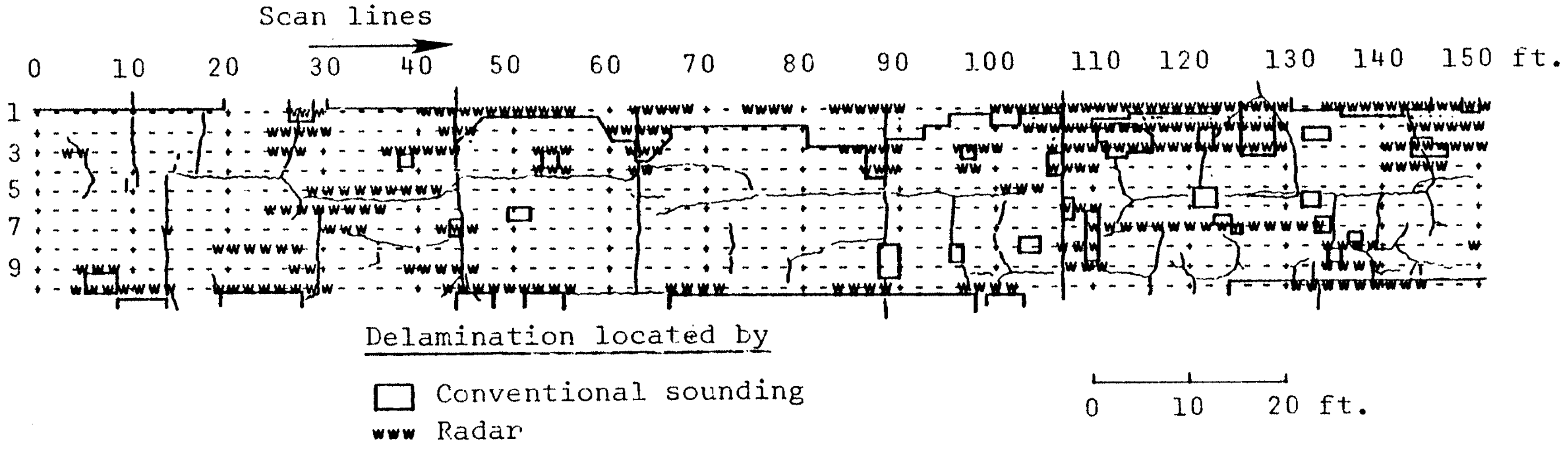


Figure 19. Test area in overlaid deck no. 2 (1 ft. = 0.3046 m).

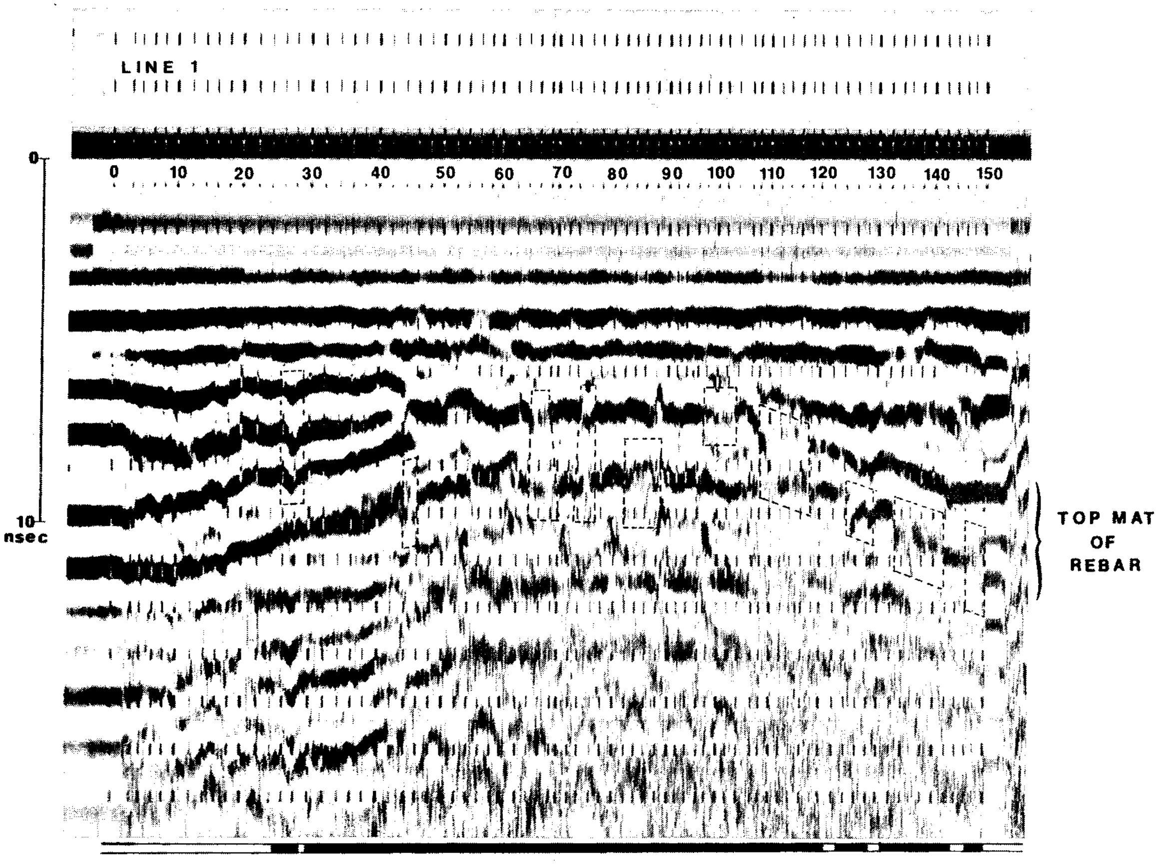


Figure 20. Radar reflection profiles for test area in overlaid deck no. 2. Notice the arch spanning each profile near the top mat of rebars.

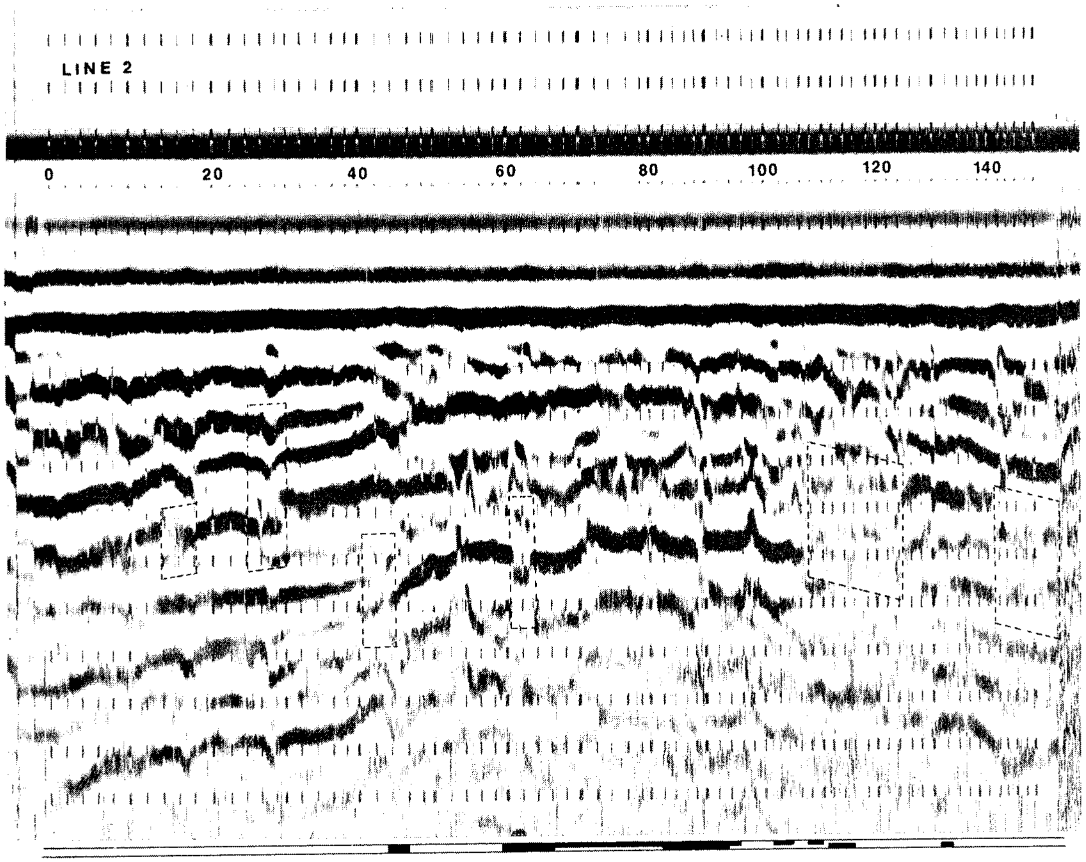


Figure 20. Continued.

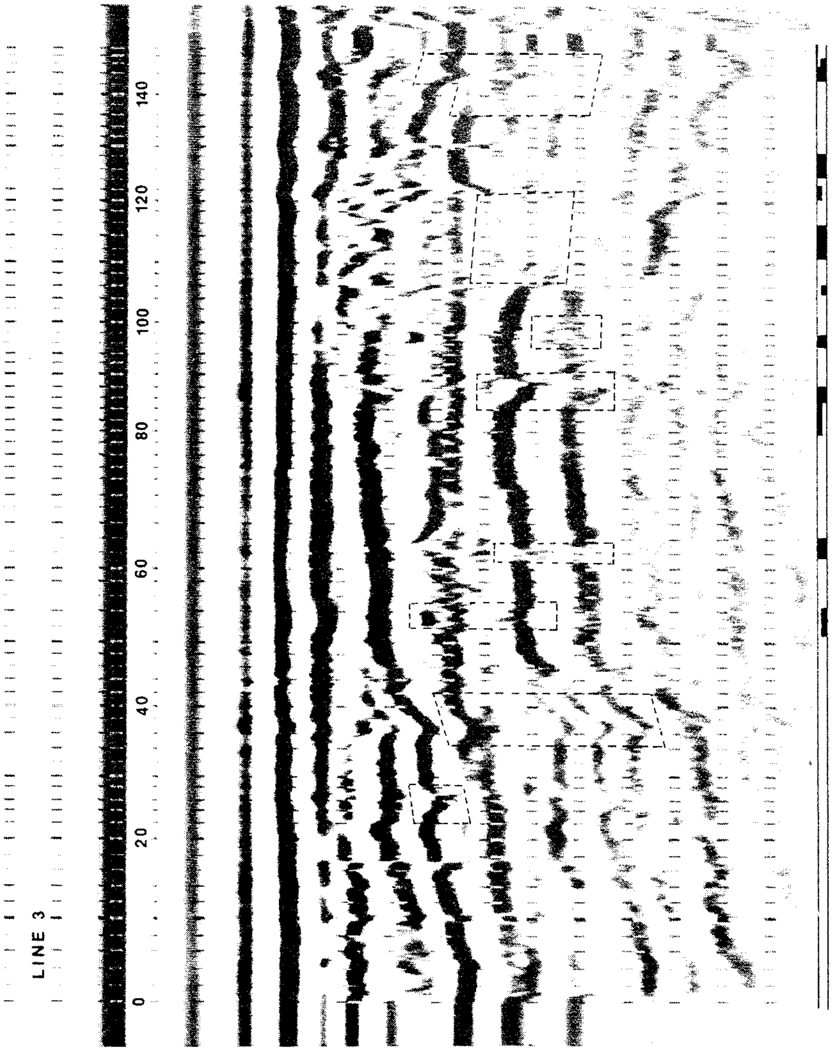


Figure 20. Continued.

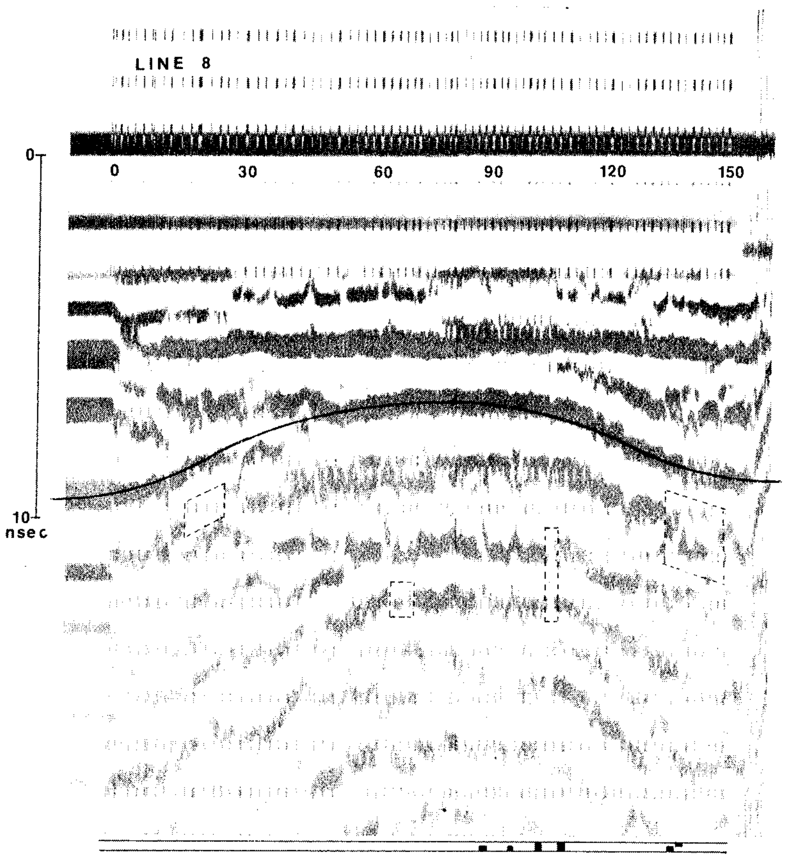


Figure 20. Continued.

Table 1

Measured Total Thickness of Overlays at Various Points and Transit Times for Overlay Deck No. 2

Location, ft.	Thickness, in.	Transit Time, nsec.
0	13.8	9.5
10	12.5	9.1
20	11.0	8.7
30	10.3	8.0
40	9.0	7.5
50	8.0	7.1
60	7.5	6.9
70	7.0	6.8
80	7.0	6.7
90	7.0	6.7
100	7.5	6.9
110	8.3	7.1
120	9.5	7.5
130	10.5	8.2
140	12.0	8.6
150	13.0	8.9

1.0 ft. = 0.305 m

1.0 in. = 2.54 cm

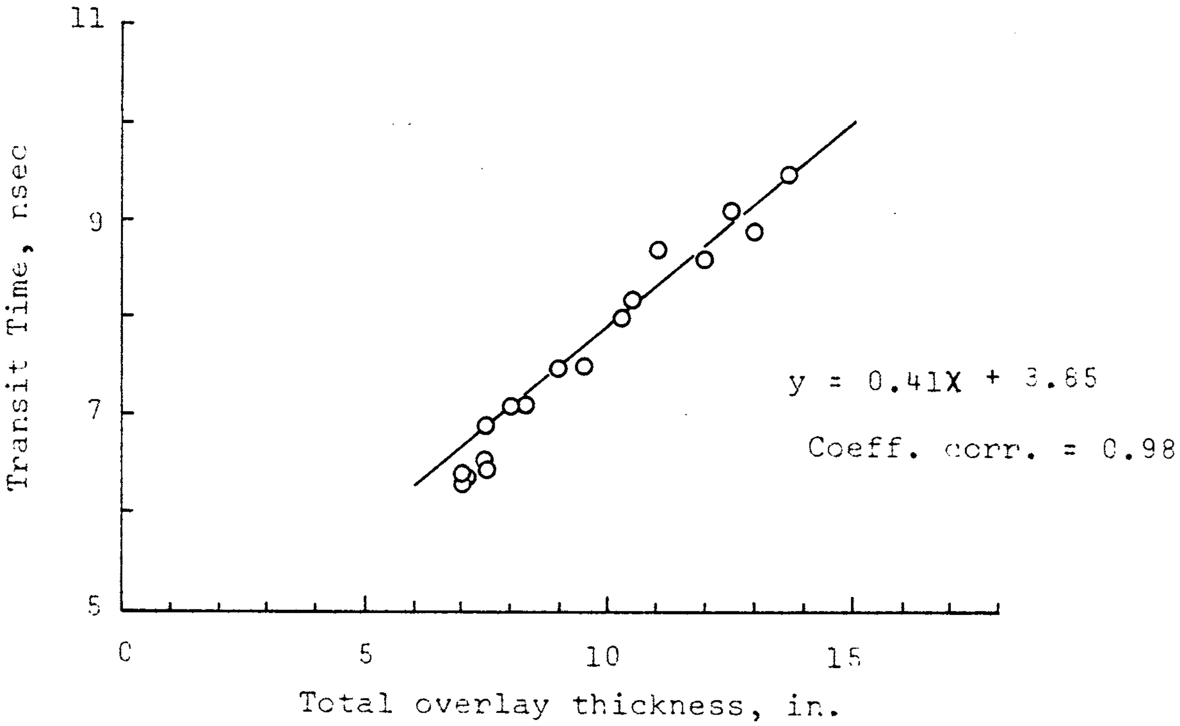


Figure 21. Relationship between total overlay thickness and transit time for overlay deck no. 2

The reflection profiles recorded for this deck were the most complicated of those recorded during the investigation. This complexity probably resulted from the arch of the deck and the accumulated layers that were disbonded at places between overlays and between the overlay and concrete. The difficulty of locating the unsound concrete would be made easier by sort of synthesizing from these complicated profiles a reflection profile in which the reflections from the arched deck are "clean" as if the overlays and concrete were perfectly bonded and sound. The resulting synthesized profile would closely resemble that illustrated in Figure 22, which the user can then compare with the actually recorded profiles to spot any irregularities such as depressions, breaks, or blurs that may represent delaminations in the concrete.

The locations of the suspected unsound concrete identified in this approach were shown in Figure 19, together with the delaminations located by sounding after removal of the overlays. There were some minor disagreements at locations where cracks in the overlay ran parallel and near the paths of the transducer; i.e., the scan lines. As was observed earlier, isolated small delaminations were occasionally missed by the radar. Nevertheless, the overall agreement was good at the least.

Overlaid Deck No. 3

Deck No. 3 was 22 ft. (6.7 m) wide from curb to curb, and consisted of three 42-ft. (12.8-m) spans with premolded bituminous expansion joints. Except for the curb-to-curb reflective cracks along the expansion joints, the overlay was free of cracks. Along each curb, a partial thickness of the overlay had spalled. The spalled strip along the top curb, shown in Figure 23, was about 1 ft. (0.3-m) wide, while that along the bottom curb was more than 2-ft. (0.6-m) wide. Because of the width of this spalled strip along the bottom curb, the first longitudinal radar scan was made 4 ft. (1.2-m) off the curb (Figure 23). Then scans were made at 2-ft. (0.6-m) intervals, with the last scan being at the 20-ft. (6.1-m) line.

As mentioned earlier, this deck has not been surveyed with conventional sounding techniques since it will not be repaired until the 1982 construction season. However, through visual examination and engineering judgement, the bridge maintenance engineer in charge of the inspection of the deck judged that some of the concrete was suspect and would probably have to be replaced. Figure 23 shows the suspected areas as taken directly from the repair plan prepared by the engineer.

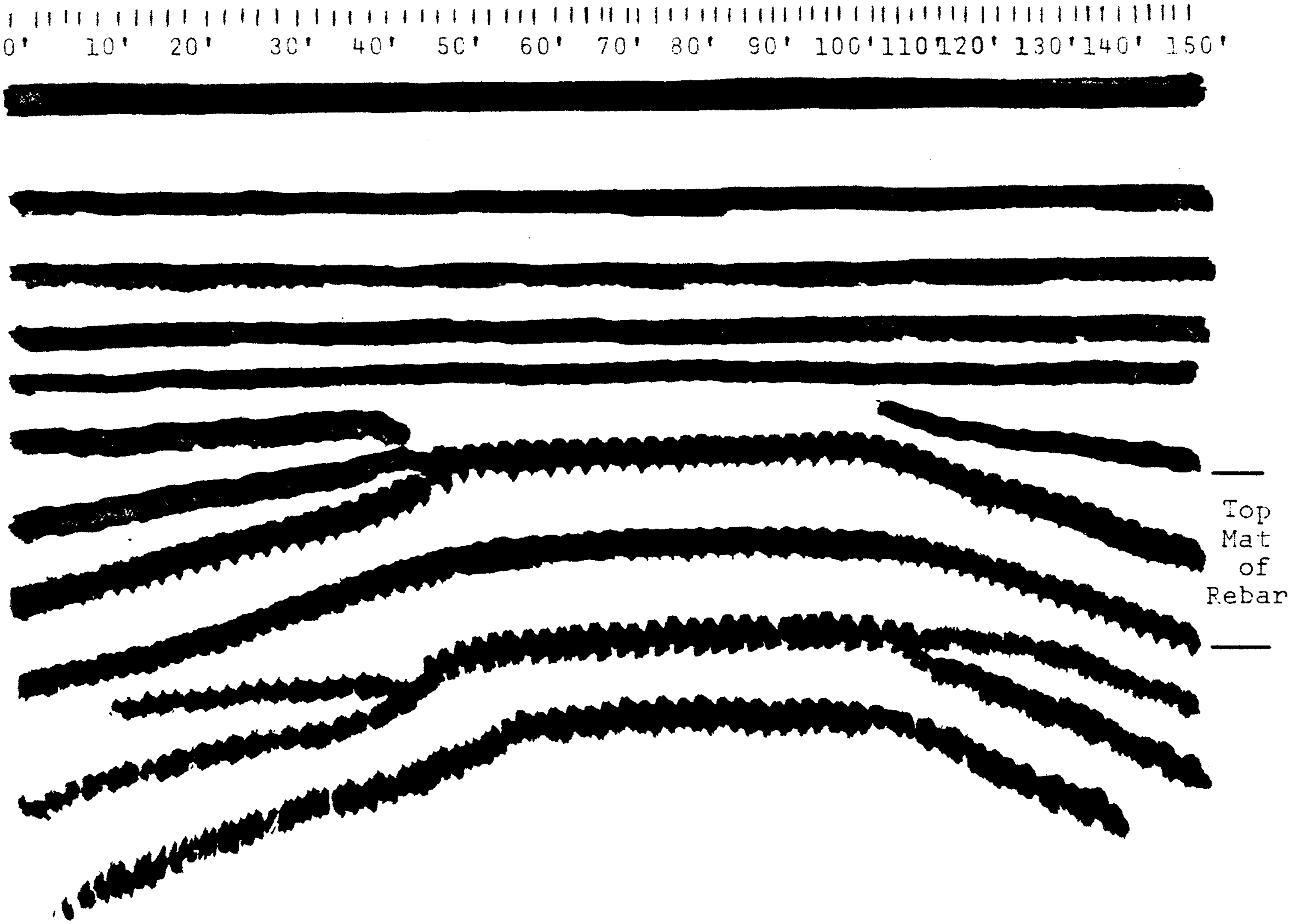
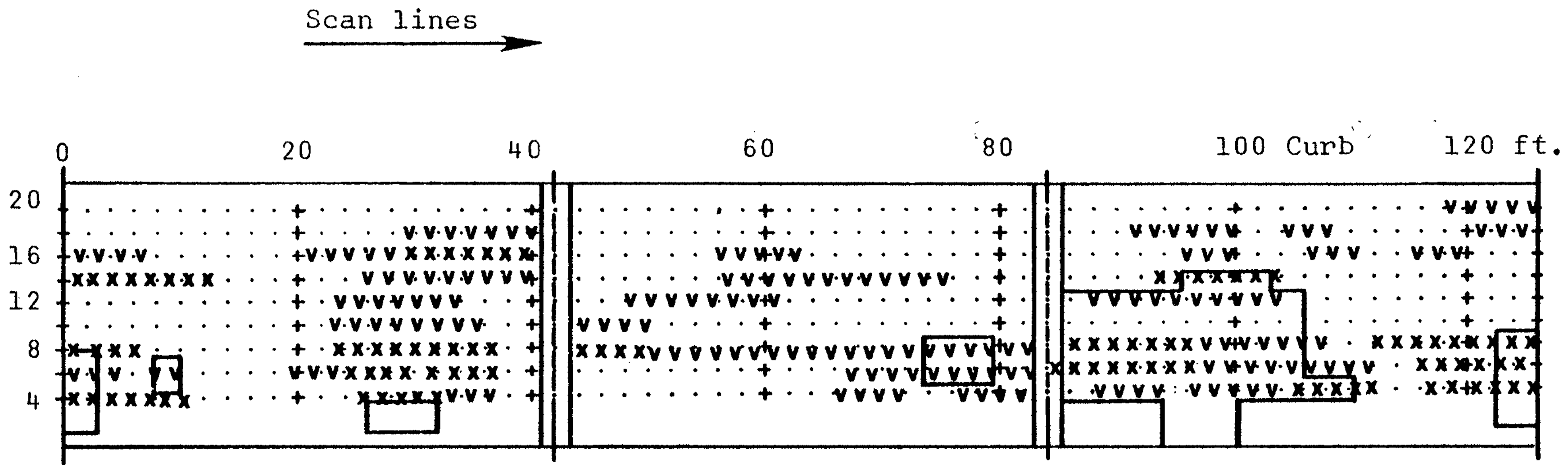


Figure 22. A synthesized radar reflection profile for an arched deck with sound overlays and concrete.



☐ Concrete judged as suspect after visual inspection

xxx Concrete judged as delaminated by radar survey

vvv Concrete judged as possibly delaminated by radar survey

Figure 23. Overlaid bridge deck no. 3.

For comparison, Figure 23 also shows the areas of concrete believed to be either definitely or possibly delaminated based on the recorded radar reflection profiles. Some of these profiles are shown in Figure 24. (The classification into definitely and possibly delaminated is to emphasize that some of the observed signatures of delamination were relatively less pronounced than others.) Since the overlay has not yet been removed to permit sounding of the deck, it isn't possible to directly determine how well the radar technique performed. However, the general agreement between the visual inspection and the radar technique shown in Figure 23 is about as good as that between conventional sounding and the radar technique that was observed in the other decks, overlaid and otherwise. Therefore, it can be inferred that the radar technique probably worked as well on this deck as it did on the others.

The clumping, vertical streaks in these reflection profiles that at times tended to obscure the reflection bands were "noises" brought about by improper adjustment of the gain and sensitivity settings on the radar instruments. These profiles and those presented earlier (Figures 17 and 18) for overlaid deck no. 1 are relatively simpler than those for the arched deck (no. 2) and are typical of what a user would often encounter. The use of a thinner asphalt dielectric block than the 10.5-in. (26.7-cm) one used would probably provide better reflection profiles for deck no. 2.

As mentioned earlier, a 2-in. (5.0-cm) asphalt dielectric spacer was also used on deck no. 3. As one of the reflection profiles recorded in this manner shows (Figure 25), there wasn't sufficient separation between the radar pulse reflections at the top mat of rebars and those reflections that preceded it. It appears that an asphalt spacer slightly thicker than 2.0 in.(5.0-cm) may be more suitable.

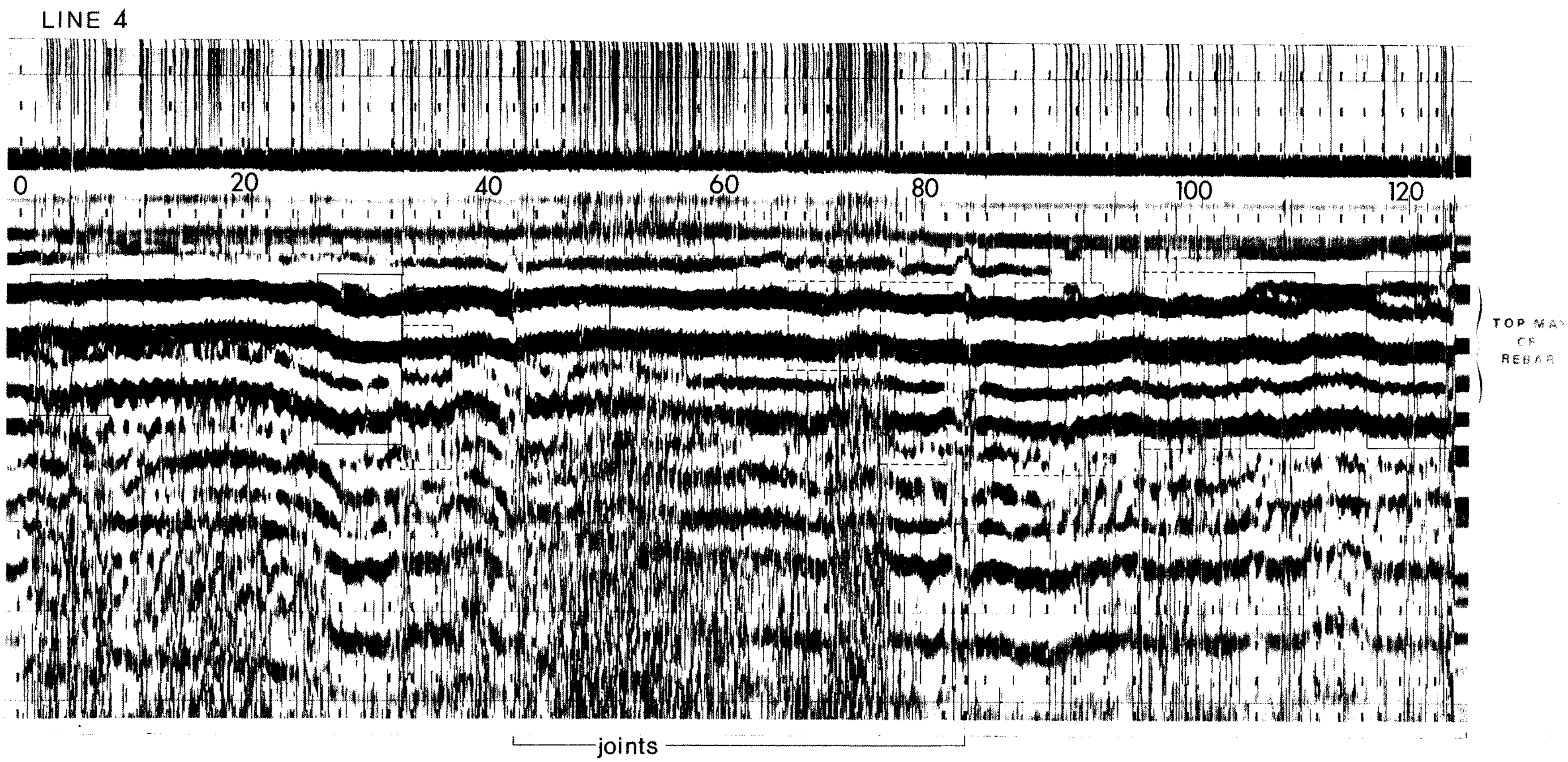


Figure 24. Radar reflection profiles for overlaid deck no. 3.

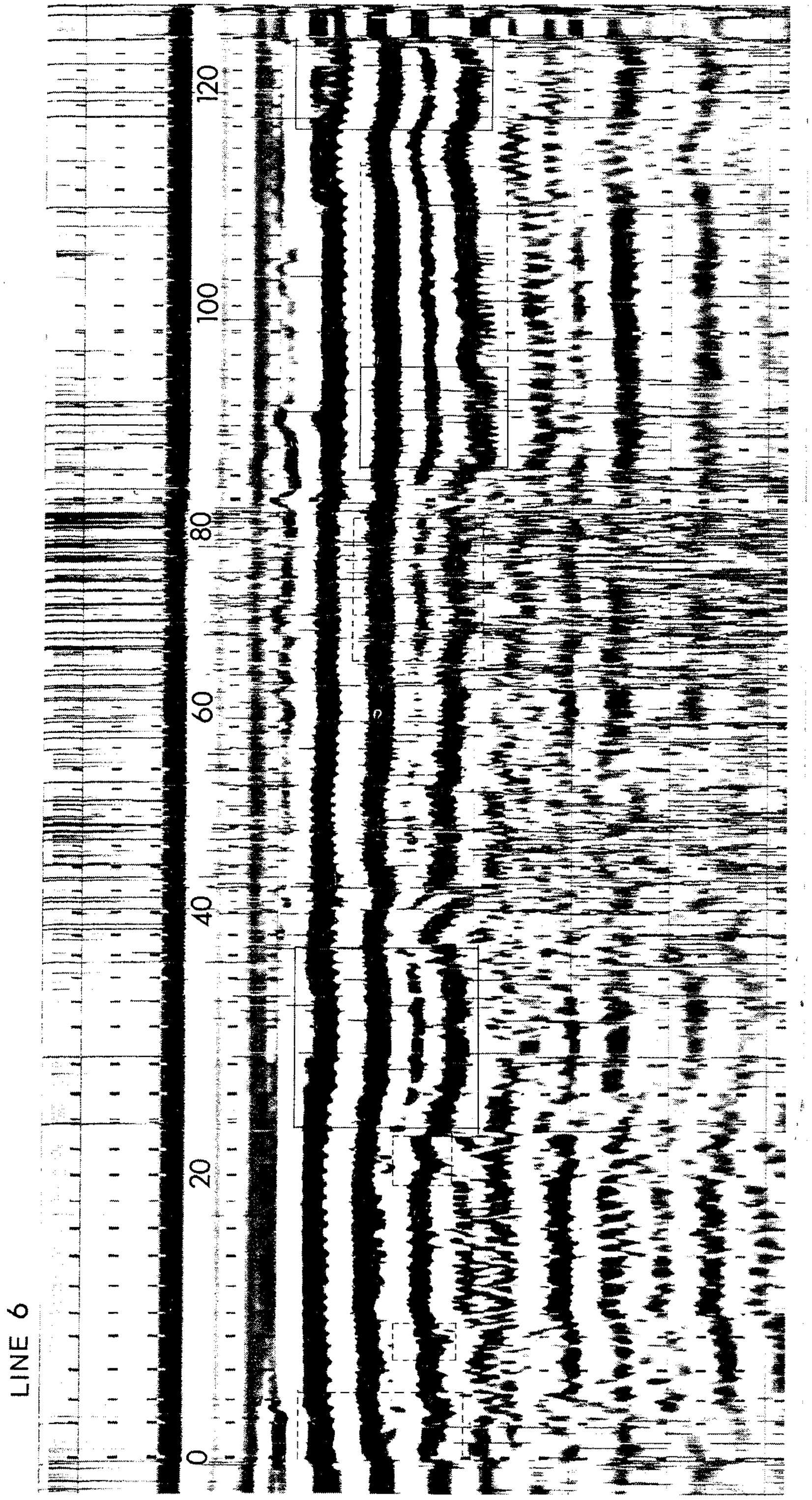


Figure 24. Continued.

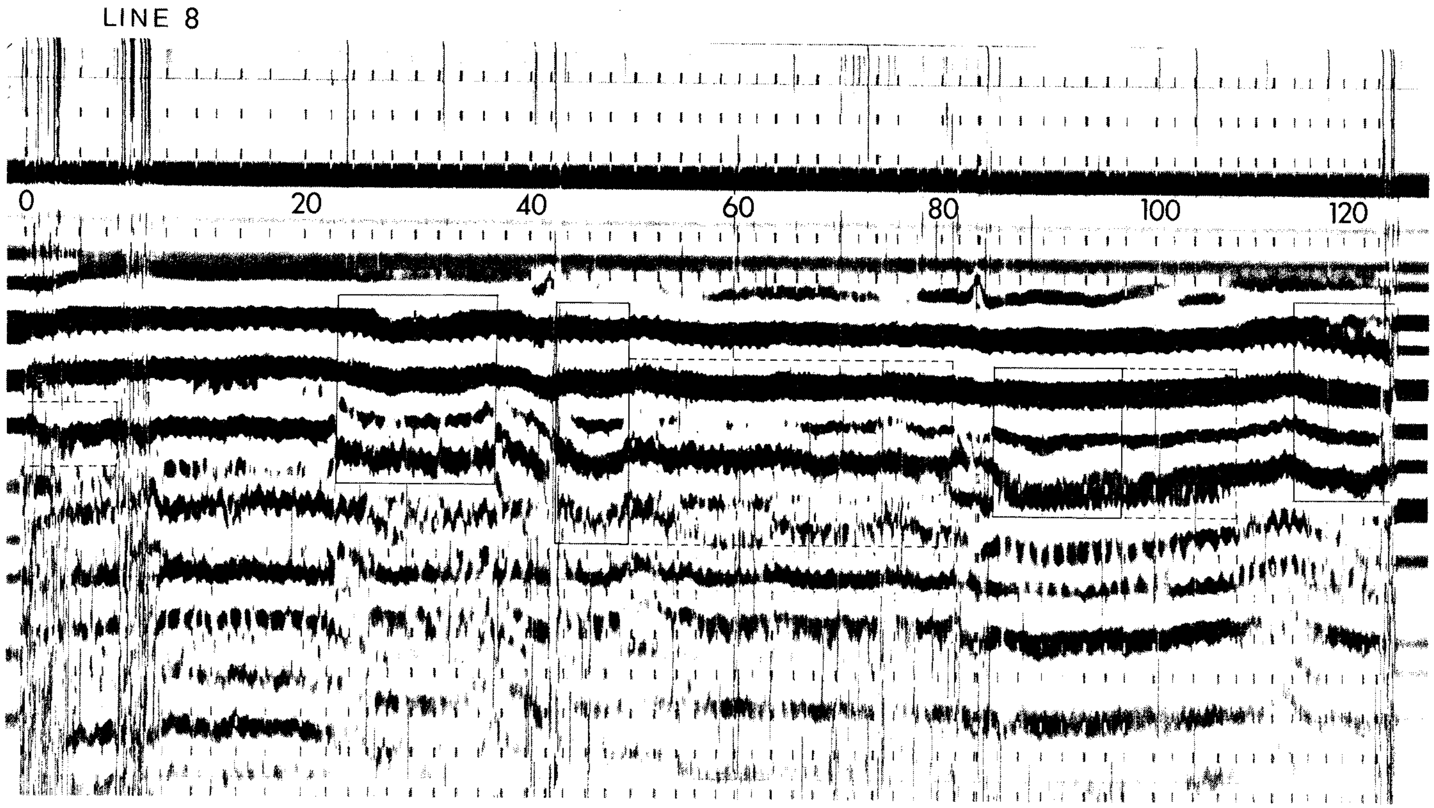


Figure 24. Continued.

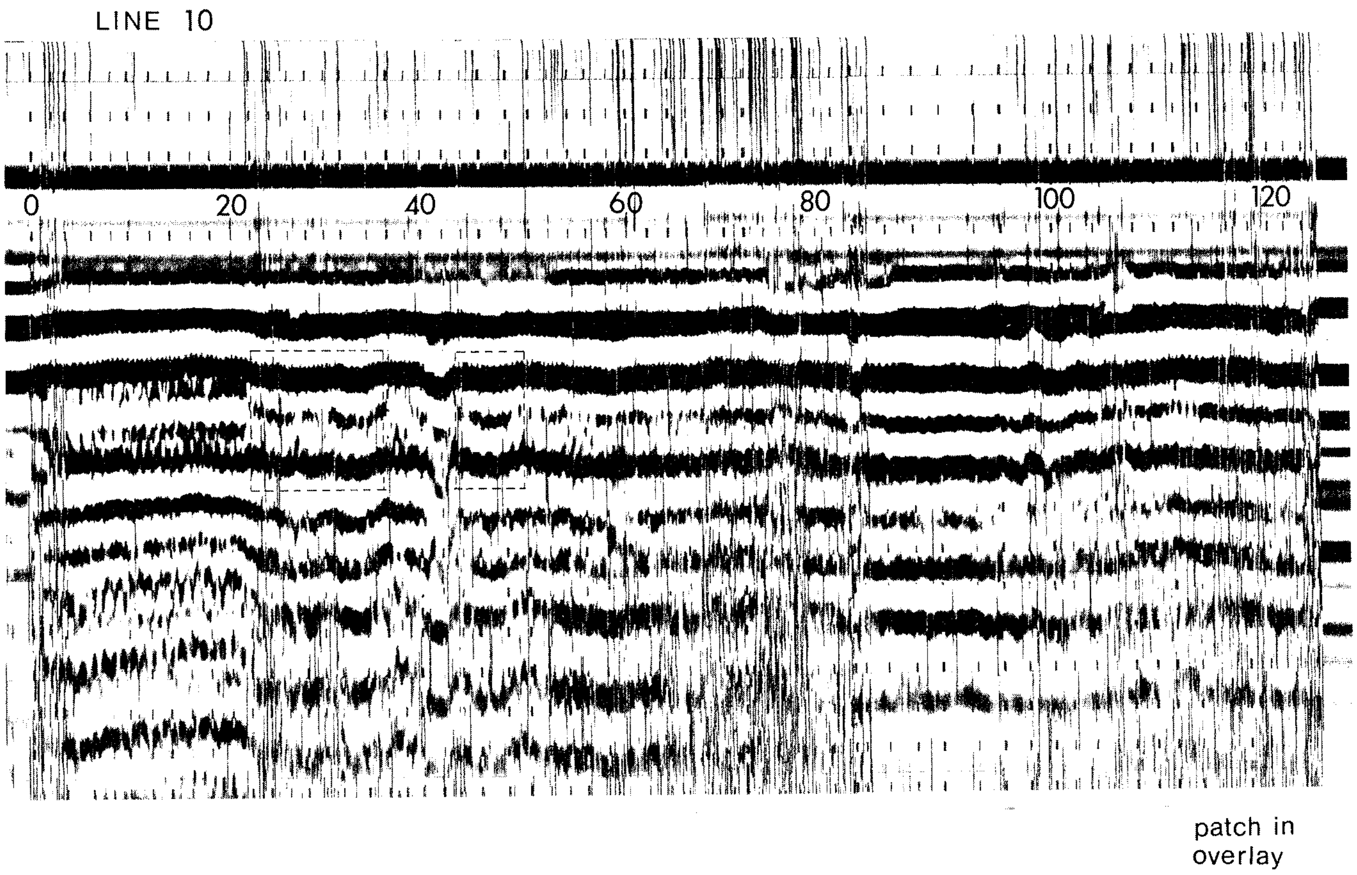


Figure 24. Continued.

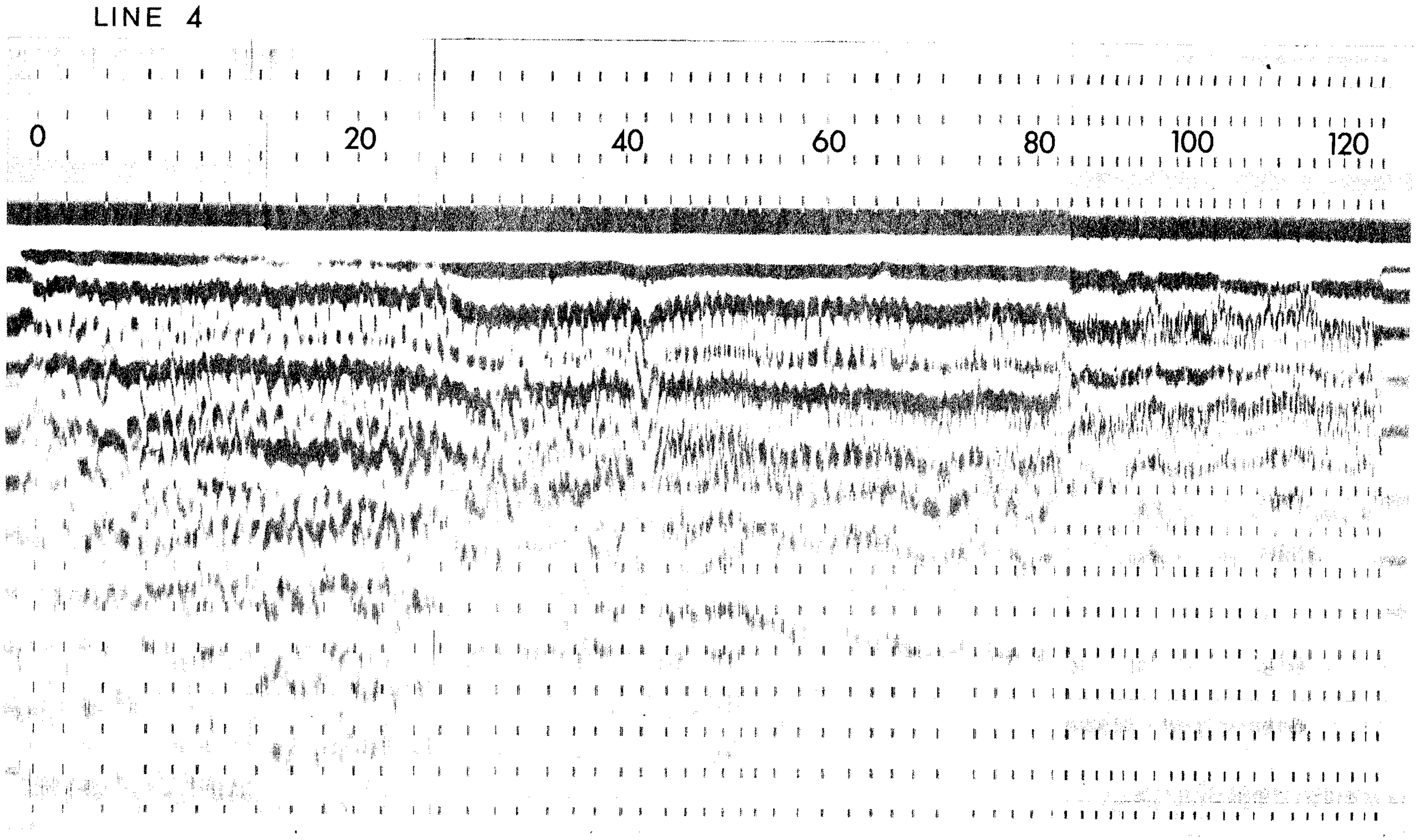


Figure 25. Reflection profile for overlaid deck no. 3 using a 2-in. asphalt dielectric spacer.

SUMMARY OF FINDINGS

The following summary can be made from the above discussion.

1. Ground-penetrating radar can be used successfully to detect concrete delamination in both non-overlaid and overlaid concrete bridge decks.
2. To ensure proper separation of the radar pulse reflection at the level of the top mat of reinforcing bars from those reflections that preceded it, a sand or asphalt dielectric spacer was used, depending upon whether the deck was non-overlaid or overlaid.
3. Concrete delaminations are manifested in radar reflection profiles as irregularities in the reflection bands corresponding to the top mat of reinforcement.
4. These irregularities, or signatures of concrete delaminations, were most often in the form of depressions, but in some instances were doublets, blurs, and/or breaks in the profiles.
5. These signatures may appear more prominently in the profiles for some decks than in those for others.
6. The radar sometimes missed small delaminated areas about 1 ft. (0.3 m) across. However, this relatively small deficiency does not impair the overall effectiveness of this technique as a suitable nondestructive method for surveying the general condition of a deck, overlaid or non-overlaid.

RECOMMENDATION

This investigation has demonstrated that ground-penetrating radar can fill the urgent need for a nondestructive technique for surveying the general condition of both non-overlaid and overlaid concrete bridge decks, and that it can become a key part of a condition survey program.

However, the procedure used in this investigation is still not as rapid as desired, with the necessity to use a dielectric spacer being the main impediment. Further work should be undertaken with a radar transducer that has just been introduced into the market and has half the clear time, approximately 0.5 nanosecond, of the 101c transducer used in this investigation. Such a narrow-pulse transducer would likely eliminate the need for a dielectric spacer and also enhance the resolution of the profiles. An alternate procedure with the radar transducer suspended in the air should also be investigated.

Also just recently introduced is a graphic recorder system that has five times the response rate of the recorder used in the present study. This faster recorder should also be tried. Together with the new narrow-pulse transducer, it should give a dramatic improvement in the speed with which a survey of bridge decks can be conducted with ground-penetrating radar.

ACKNOWLEDGEMENT

The author expresses appreciation for the cooperation extended by Peter A. Kopac of the Federal Highway Administration's Materials Division and District Engineers R. H. Morecock, F. L. Prewoznik, W. L. Sellars, and J. A. Tavenner and their respective staffs. Special thanks go to Assistant Resident Engineers W. B. Coburn and H. S. Northington and their staffs for their valuable assistance.

Appreciation is extended to P. Hague of Geophysical Survey Systems, Inc. for valuable suggestions and the review of this report.

The author extends gratitude to J. C. Stulting and, especially, C. E. Giannini, Jr. of the Council staff for their valuable assistance.

Acknowledgement is due Arlene Fewell for her typing assistance, and to H. T. Craft and his unit for editing and reproducing the report.

The study was conducted under the general guidance of H. E. Brown and financed with HPR funds administered through the Federal Highway Administration.

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