Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VA-93-R20		

4. Title and Subtitle	5. Report Date
The Use of Ground-Penetrating Radar in the Surveying of Overlaid Bridge Decks	June 1993
	6. Performing Organization Code
7. Author(s)	8. Preforming Organization Report No.
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9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Virginia Transportation Research Council Box 3817, University Station Charlottesville, Virginia 22903-0817	11. Contract or Grant No. HPR #98-011
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Virginia Department of Transportation 1401 E. Broad Street Richmond, Virginia 23219	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

none

16. Abstract

It was shown in a previous study that the presence of delamination in concrete can be detected by the appearance of a distinctive signature in the analog radar reflection profiles recorded when a concrete deck is scanned with ground-penetrating radar. As a follow-up, radar was used on eleven overlaid bridge decks to assess the overall reliability of the technique when applied to the nondestructive inspection of such decks, using the identified radar signature as an indicator of the presence of concrete delamination. The radar results were verified by soundings conducted on the test decks after their overlays were removed.

Among the decks tested, the average success rate of radar in detecting real concrete delamination was found to be 82 ± 20 percent (at 95 percentile). In addition, false indication of the presence of delamination had been observed. It was suspected, however, that the presence of debonding and damage in the overlay in some locations contributed extensively to this type of errors since such damages in the decks would likely manifest themselves as anomalies in the reflection profiles close to that associated with concrete delamination. On the other hand, although some concrete delaminations were missed by radar, these misses often involved relatively small delaminated areas.

For future studies, it is recommended that additional radar parameters (including localized increased reflectivity at the bituminous/concrete interface, polarity change in the reflection at the interface, distortions in the reflection from the rebars, and attenuation of reflection from the concrete slab) be examined. These parameters can be related to other types of damages often found in overlaid decks in conjunction with the concrete delaminations.

17. Key Words	18. Distribution Statement
overlaid bridge decks, inspection, concrete delamination, ground-penetrating radar	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Clasif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	

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1563

SUMMARY REPORT

THE USE OF GROUND-PENETRATING RADAR IN THE SURVEYING OF OVERLAID BRIDGE DECKS

Gerardo G. Clemeña, Ph.D.
Principal Research Scientist

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

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

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

Charlottesville, Virginia

June 1993
VTRC 93-R20

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INTRODUCTION

To aid in the assignment of priorities in the maintenance of bridge decks, bridge engineers need reliable data from routine surveys of the condition of the decks. For surveying the extent of concrete delaminations caused by rebar corrosion in decks that do not have bituminous overlays, inspection methods such as sounding with chains and the measurement of half-cell potential are available. Although these methods are relatively time-consuming and require lane closure, they are quite effective.[1] If lane closure is not possible, which is often the case in major urban areas, noncontact and nondestructive techniques such as infrared thermography and ground-penetrating radar can be utilized, and they are gaining wide acceptance.[2, 3]

For overlaid bridge decks, sounding with chain drags and the measurement of half-cell potential are practically useless, and the effectiveness of infrared thermography is at best questionable. This lack of a satisfactory inspection method for overlaid decks has forced engineers to rely on visual inspections of the overlay and the underside of a deck, which is very ineffective. Engineers are hesitant to use coring because of the destructive nature of the procedure. I believe that this hesitancy leads to the extraction of an insufficient number of cores from a deck, which renders the results statistically unreliable for estimating the extent of deterioration in the deck. Because of this, budgeting of maintenance funds for the rehabilitation of such decks is very difficult.

In recognition of this need for a rapid, nondestructive inspection method for overlaid bridge decks, all potentially applicable techniques being used in various other industries were assessed, and it was concluded that ground-penetrating radar (GPR) had the best potential for fulfilling this need.

PURPOSE AND SCOPE

This report describes briefly the principle of GPR. (A more thorough discussion of the principle of GPR is presented elsewhere[4]). In addition, it summarizes the results of an attempt to assess the effectiveness of radar for inspecting overlaid

1072

bridge decks based on the data obtained from several decks between 1983 and 1985, and it recommends further research that could improve the effectiveness of GPR.

METHODOLOGY

Principle of Ground-Penetrating Radar

When electromagnetic energy (such as a microwave, the frequency of which can range from 0.3 to 300 GHz) is beamed into an object that consists of materials of different dielectric properties, a portion of the beam is reflected at each interface between these materials. The remainder of the beam penetrates into the second material until it encounters another interface where another reflection occurs. The extent of reflection at each interface is determined by the difference between the dielectric constants of the two materials at the interface.

For a material system such as an overlaid concrete deck (Figure 1), reflections will occur typically at the air/bituminous interface (i.e., the top surface of the deck), then the bituminous/concrete interface, the steel/concrete interface, and finally the concrete/air interface (i.e., the bottom surface of the deck). If there are delaminations in the concrete, usually around the top mat of steel reinforcement, additional reflections can be observed. Such additional reflections serve as an indicator of the presence of concrete delamination. Each of these reflections reaches the antenna at an arrival time that is determined by the thicknesses of the bituminous overlay and the concrete that the microwave pulses have to traverse and the respective propagation speeds of the microwave through these materials. The propagation speed in each material is in turn inversely influenced by the dielectric constant of the material involved.

Instrumentation

The GPR system used in this project was the dc-powered SIR 4400 and the 101c transducer, which are manufactured by Geophysical Survey Systems, Inc. (This system was used because it was available on loan from the Virginia Department of Transportation[5]). The transducer (or antenna) acts both as a transmitter and a receiver. It transmits bursts of microwave energy at a rate of 50 KHz with a central frequency of 900 MHz and a pulse width of approximately 1.1 nanosecond (10^{-9} second; ns). An EPC 2208 facsimile graphic recorder was used to record the microwave reflected from the decks during the survey (Figure 2).

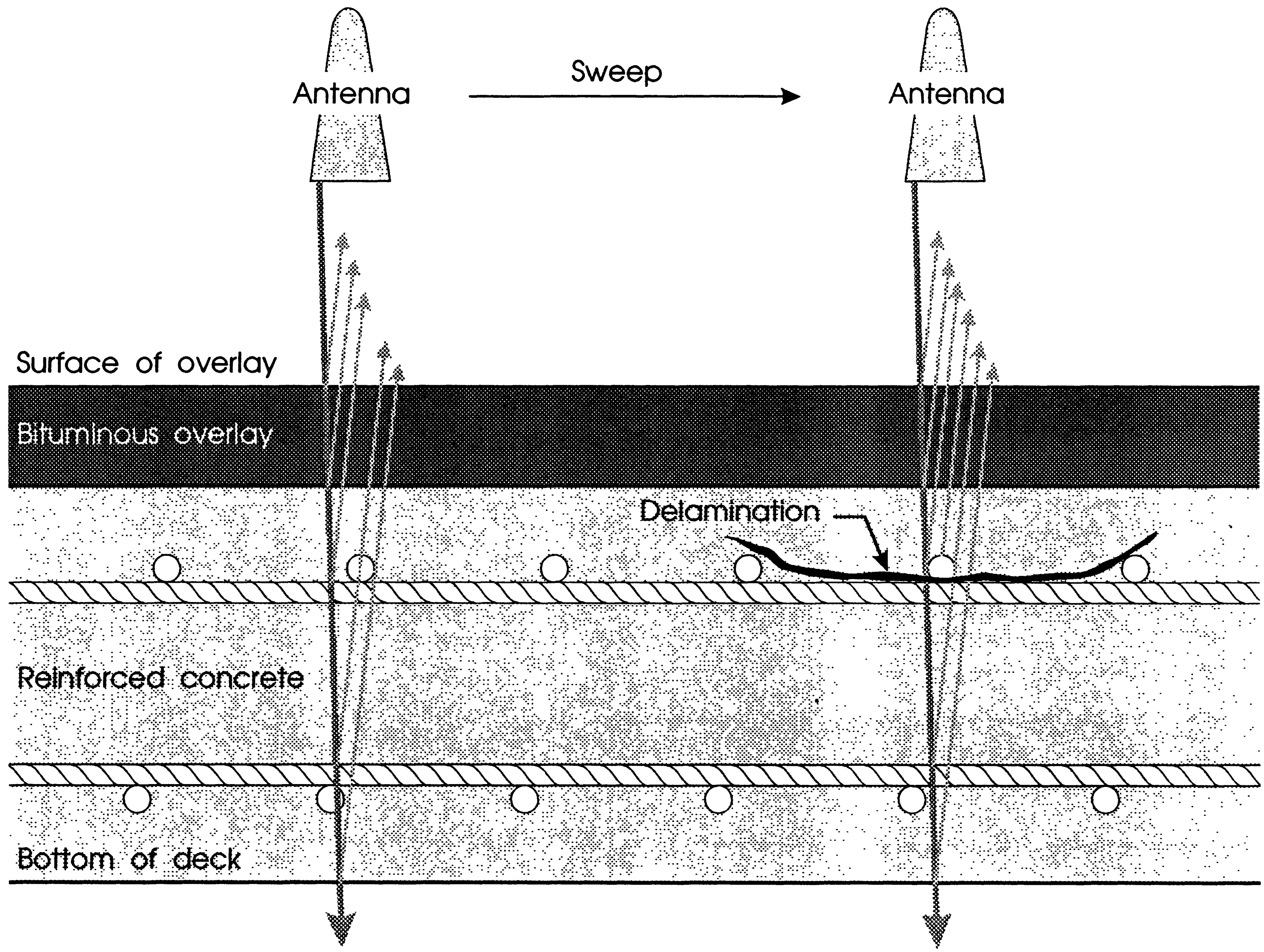

Figure 1. Radar reflections from the cross section of an overlaid concrete deck. The presence of concrete delamination causes additional reflection of the incident microwave pulses.

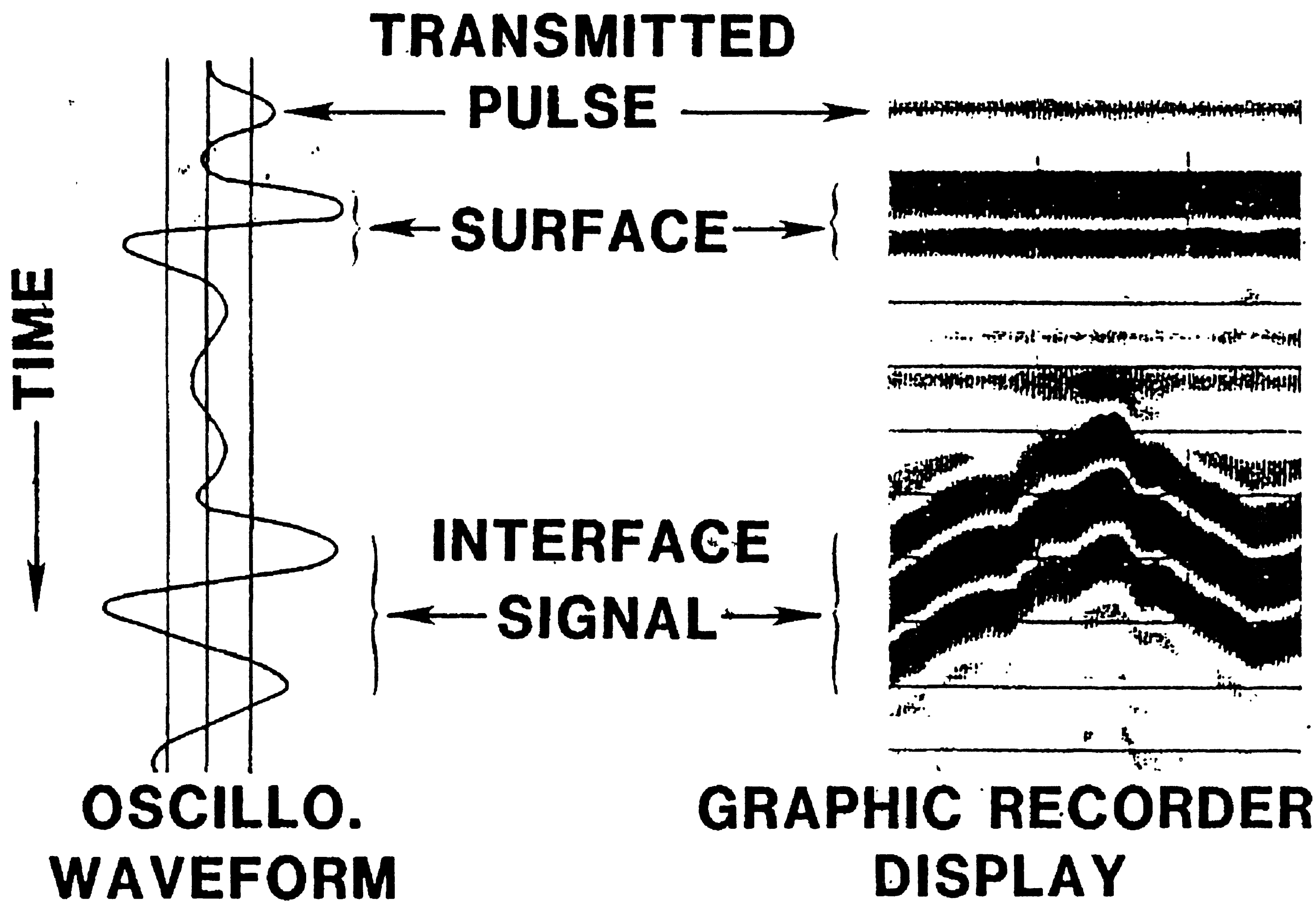

Figure 2. Data from ground-penetrating radar.

Survey Procedure

Radar Survey

In order to be able to recognize any concrete delamination that may have been detected by the antenna and recorded in a chart recording of reflections from a deck, it was necessary to identify the radar signature of typical concrete delaminations. A *radar signature* is a unique feature of the pattern of electromagnetic reflections. For the purpose of identifying this signature, two concrete decks with known delaminations (as detected by sounding with chains) were partially scanned with the GPR antenna.

Following this task, 11 overlaid bridge decks (that were already scheduled for repair) were scanned with radar while the overlay on each deck was still intact. This scanning consisted of making longitudinal passes over each deck with the radar antenna, keeping the transverse spacing between passes or scans at 2.0 ft (0.61 m). This spacing was used because the antenna has a coverage of approximately 1.5 ft (0.45 m) across.

Verification of the Condition of the Concrete

To verify the radar results, the actual condition of the concrete in each deck had to be determined. This was obtained by sounding each deck with chain drags after the overlay was removed during the repair. A 2.0-ft (0.61-m) square grid was utilized on each deck to accurately map any concrete delamination and vertical crack to within 3 in (7.5 cm).

Sounding with chain drags and other suitable tools gives quite accurate results for bare concrete decks.[6] As long as interference from traffic noise is tolerable, the difficulty with sounding lies not in detecting the delamination but in delineating its boundary. It is estimated that the uncertainty involved can be at least ± 0.5 ft (15 cm).

DISCUSSION OF RESULTS

Interpretation of Radar Reflection Profile

Figure 3 shows a reflection profile recorded as the antenna scanned along the length of span No. 1 of deck No. 1 18.0 ft (5.5 m) from one curb. This profile actually consisted of numerous individual reflection waveforms that were continuously recorded (one beside the next and from left to right on the chart) as the antenna passed over the deck.

Each waveform consisted of microwave pulses reflected from the various interfaces found typically in an overlaid deck. The shape of each waveform is

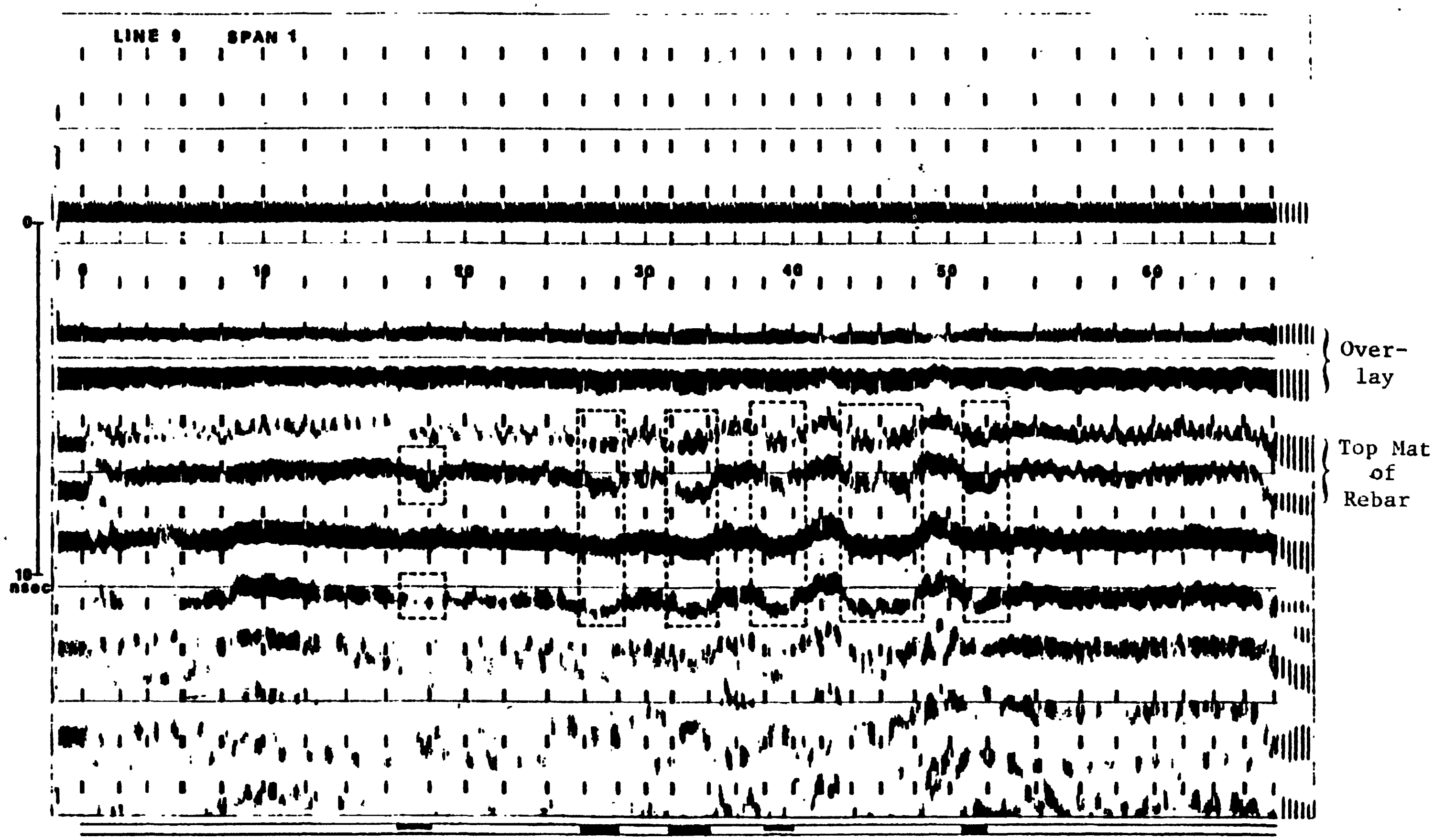

Figure 3. A radar reflection profile for a deck area in span No. 1 of overlaid deck No. 1. (The dashed rectangles outline the irregularities in the reflection bands for the top mat or rebars. The shaded rectangles at the bottom of the illustration denote the locations of concrete delaminations found in the area by chain drags after the overlay was removed.)

characterized by the arrival time and the amplitude of each of these reflected pulses. As Figure 2 shows, the dark bands in the reflection profiles in Figure 3 correspond to the positive and negative peaks of each reflected pulse, and the white bands are the zero crossings between peaks (i.e., where radar signal amplitude changes from positive to negative or vice versa). The horizontal distance on the chart corresponds to the longitudinal location on span No. 1 of deck No. 1 at 18.0 ft (5.5 m) from one curb. The vertical scale corresponds to the arrival time of reflected pulses in nanoseconds.

The interpretation of such a reflection profile can be made easier by identifying which bands are associated with reflection from the top mat of reinforcement. This is because most concrete delaminations originate there. Examining Figure 3, one can observe that, at approximately 6 ns (i.e., around the fourth and fifth bands), the reflection pattern assumed the shape of pointed blips. These blips characterize reflections from the rebars, which have a relatively small cross section; therefore, they would serve as a useful indicator of such reflections. Searching for irregularities along these reflection bands, one can see six depression features that correspond to concrete delaminations. This feature has been verified to correspond to concrete delaminations in bare concrete decks. This feature is interpreted to be a result of either an additional reflection interface resulting from a severe delamination in the concrete or an increase in the travel time (as a result of a decrease in the propagation speed) of the microwave pulses reflecting from the rebars as they traversed the layer of concrete that covered the top mat rebars. The decrease in the propagation speed is a result of an increase in the dielectric constant of that layer of concrete, which in turn is likely the result of the intrusion of moisture and deicing salts. Since this depression feature had often been observed to be associated with concrete delaminations in both types of concrete decks, it was used as an indicator of the presence of concrete delaminations in the overlaid decks that were surveyed in this study.

Assessment of the Effectiveness of GPR

Using the depression feature as an indicator, the deck area represented by the radar profile in Figure 3 had six delaminated areas. Sounding of the deck area after the removal of the overlay, indicated that there were actually only five concrete delaminations, and the anomaly at tick marks 44 and 48 wasn't found. The results for this small section of deck serve to illustrate that radar can detect concrete delaminations underneath a bituminous overlay and can also give an indication of delamination where there isn't one. This type of error would, of course, cause overestimation of the quantity of delamination present in a deck.

The occurrence of this type of error suggests that the radar signature used may in some situations also be associated with other types of deteriorations that are often found in overlaid concrete decks, which include deteriorations of the top of the concrete and the bottom of the overlay. Unfortunately, such deteriorations couldn't be detected and verified once an overlay is removed since the process not only removes the overlay but also at least a 0.25-in (0.6-cm) portion of the concrete. Coring, which is a better method for verifying the actual condition of a deck at any given location, was considered but not utilized because of concern with its adverse effect on a deck.

Figure 4, which shows the results of both radar and sounding for two deck areas, illustrates that, in addition to errors relating to false indication of concrete delamination, errors involving failure by radar to detect real concrete delaminations were observed too, although, in general, the delaminations missed by radar were relatively small delaminations (of approximately 1.0 ft [30-cm] across and less). This second type of error would in contrast to the first type lead to underestimating the quantity of concrete delamination present in a deck.

To assess the extent that these two types of errors were encountered, the effectiveness of radar in detecting real concrete delamination, E, can be defined as

$$E\ (\%) = C1 \times 100 / (C1 + C2),$$

where C1 = the total linear feet of real delamination found by both radar and sounding, and C2 = the total linear feet of real delamination found only by sounding. C2 represents the amount of misses by radar. And, when the misses observed in each deck are compared with the false indication of delamination made by radar in the same deck, the "net" overestimation of delamination made by radar, NO, can be estimated by

$$NO\ (\%) = [(C3 - C2) \times 100] / (C1 + C2),$$

where C3 = the total linear feet of delamination found only by radar, i.e., false indication by radar.

In accordance with these definitions, the effectiveness of radar was assessed. The results (see Table 1) indicate that radar was able to detect, on the average, 82 ± 20 percent (at 95 percentile) of the real delaminations. When compared to the current practice of using visual inspection to "guesstimate" the amount of concrete deterioration underneath an overlay, these results should be considered at least encouraging.

However, the effectiveness of radar on three decks was only 63 to 69 percent, whereas in the remaining eight decks, the effectiveness was considerably better, at 80 to 96 percent. This variability is large and needs to be reduced — a reasonable goal may be ± 5 percent (at 95 percentile) or slightly better. As indicated earlier, an examination of the results from individual decks indicated that many of the radar's misses involved either relatively small delaminations or were actually partial misses of individual delaminations, i.e., failure not in detecting the presence of an individual delamination but in accurately delineating its size. Some good examples of both types of misses are illustrated in Figure 4.

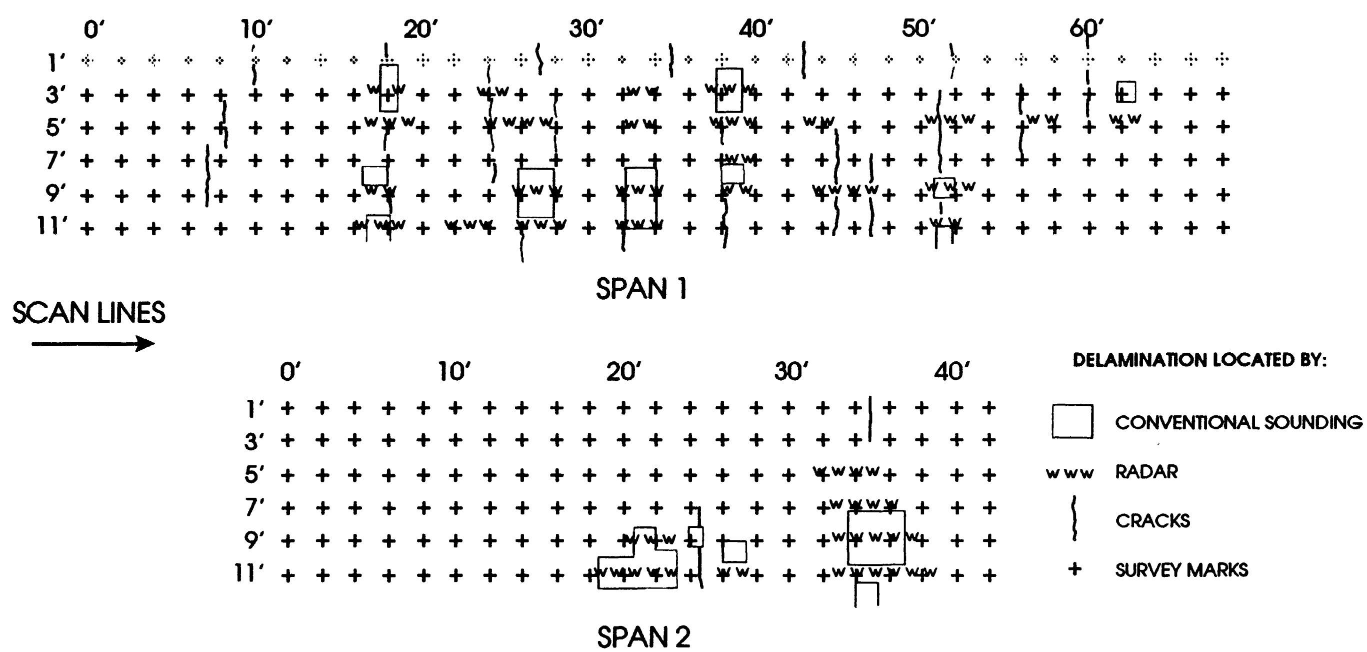

Figure 4. Test areas for overlaid deck No. 1.

Table 1
ANALYSIS OF GPR PERFORMANCE

	Linear Feet of Delamination Located by					
Deck No.	Radar and Sounding (Cl)	Sounding Only (C2)	Radar Only (C3)	Total Delam. (C1 + C2)	Effectiveness of Radar (%)	False Indication by Radar (%)
1	120	30	55	150	80	17
2	250	145	130	395	63	–4
3	500	115	225	615	81	18
4	430	50	110	480	90	13
5	121	54	92	175	69	22
6	250	37	62	287	87	9
7	24	1	72	25	96	284
8	393	20	0	413	95	–5
9	390	184	71	574	68	–20
10	51	10	36	61	84	43
11	533	88	38	621	86	–8
				Average	82	33
				Minimum	63	–20
				Maximum	96	284
				Std. Dev.	10	81

Table 1 also shows that the radar indicator gave negative net overestimations in four decks, i.e., made more misses than false indications of delaminations. Using the radar data for these decks, an engineer would have underestimated the total amount of concrete delamination by 4 to 20 percent. In the other 65 percent of the decks, however, there were more false indications than misses. The extent of the net overestimation of delamination in these decks varied, in general, inversely with the general condition of the decks (as measured by the total real delamination detected). For the two decks in the best overall condition, the overestimation varied from 43 to 248 percent; however, when expressed in the absolute terms of feet of delamination, these overestimations translate into small quantities. The overestimations in the remaining decks ranged from 9 to 22 percent of the total real delamination found in the decks.

Many of these false indications attributed to concrete delamination actually involved areas where vertical cracks were found in the concrete and the radar yielded positive results (some are illustrated in Figure 4). Unfortunately, vertical cracks in the concrete were not treated as a concrete delamination in the analysis because of the inherent difficulty in defining the horizontal boundary of the defect. Therefore, those concrete areas where vertical cracks were found and the radar indicated the presence of abnormalities were categorized against radar as C3, i.e., false indications by radar, even though those areas may actually be considered deteriorated and requiring repair.

It is suspected that another factor that may have contributed to the false indication or overestimation by radar was the unverified presence of other types of teriorations in the decks tested, such as debonding of the overlay from the concrete and/or damage to the bottom of the overlay (due to freezing and thawing of trapped moisture or water). The latter is often accompanied by deterioration of the surface of the concrete. When the concrete cover over the top mat of rebars is less than 3.0 to 3.8 in (7.6 to 9.6 cm) thick, which is the case in all existing decks, it is extremely difficult to resolve the radar reflections associated with these deteriorations from those associated with concrete delamination. This shows the need to extend targets of radar surveys to include other types of deterioration, such as the debonding of the overlays from the concrete, damage at the bottom of the overlays and the top of the concrete, and damage to concrete below the top-mat rebars. In view of this and the wide fluctuations in both types of radar errors observed among the decks surveyed, additional radar signatures that can be related to these various types of damage occurring in overlaid decks should be investigated. Such signatures may include changes in the reflectivity and/or polarity of the reflection from the bituminous/concrete interface, distortion in the reflection from the rebars, and attenuation (in amplitude) of reflection from the bottom of the concrete slab. With the exception of the distortion in the reflection from the rebars, which would arise from corrosion-induced loss in cross section of the rebars, these changes can arise from the intrusion of moisture into the decks.

CONCLUSIONS

1. GPR showed promise as a powerful method for the inspection of overlaid concrete bridge decks.

2. The localized decrease in propagation speed of microwave pulse in the layer of concrete above the top mat of rebars appeared to be a signature of delaminations in the concrete around these rebars. Use of this signature alone to detect delamination yielded an average success rate of 82 ± 20 percent, at 95 percentile.

3. However, the wide variation in the success rates (with 63 to 69 percent for three decks and 80 to 96 percent for the rest of the decks tested) and the errors made by radar (such as false indications of the presence of concrete delamination and failure to detect some delaminations) suggest that additional radar signatures need to be identified for possible application.

4. In addition to the detection of concrete delamination in overlaid decks, the other types of deterioration that are often encountered in such decks should also be included in future studies.

5. If one considers that without radar there would actually be nothing quantitative for an engineer to rely on, these results have to be viewed as encouraging.

RECOMMENDATIONS

Proper interpretation of the radar signals is essential to the successful use of GPR in the inspection of overlaid decks. The mixed success of this study pointed out the difficulty underlying the interpretation of radar signals. This difficulty exists because our understanding of the manner in which microwave pulses propagate in the materials of an overlaid concrete bridge deck and the effects of the different types of damage that can occur in this system on this propagation is still inadequate. It is, therefore, recommended that additional radar signatures (including localized increased reflectivity at the bituminous/concrete interface, polarity change in the reflection at that interface, distortions in the reflection from the rebars, and attenuation of reflection from the concrete slab) be examined in future studies in conjunction with the other types of damage that are found in overlaid decks.

Another essential element to the success of this technique is the use of a suitable radar system. It is believed that the radar system used in this study is more suitable to geophysical applications. A more sensitive system is needed for bridge deck inspections. The bipolar nature of the reflected pulses (see Figure 2) as constructed and presented by the electronics of the system adds to the complexity and, therefore, the difficulty in the interpretation of the radar profiles. The design of the antenna also resulted in a mismatch of the impedances of the air and the antenna, which requires the use of a bituminous block (as a spacer) between the antenna during a survey. For these reasons, it is recommended that a more suitable radar system be used in any further study.

To facilitate the examination of other possible signatures of damage in overlaid decks, it is also recommended that an adequate high-speed signal data acquisition system be utilized to record and store radar reflection signals in digitized form. The development of software that will allow computerized examinations of these radar signatures using the digitized radar signals is also recommended. It is envisioned that computerization of radar surveys will be a necessity anyway because of the sheer volume of data that is involved in the survey of bridge decks (not to mention pavements for which radar also has different potential applications).

ACKNOWLEDGMENTS

The author extends his appreciation to K. N. Black of the Federal Highway Administration and Michael M. Sprinkel and J.P. Gomez of the Research Council for reviewing this report, to C. E. Gianinni for his valuable assistance, to Roger Howe for editing the manuscript, to Randy Combs for the graphic artwork, and to Arlene Fewell and Linda Barsel for preparing and laying out the text.

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