# Nondestructive Inspection of Overlaid Bridge Decks with Ground-Penetrating Radar

#### GERARDO G. CLEMEÑA

An ongoing study on the use of ground-penetrating radar for the nondestructive inspection of overlaid concrete bridge decks is described. The technique, which uses microwave pulses, should be particularly valuable in the inspection of box-girder and similar types of decks for which even the undersides are inaccessible for visual inspection. The study has indicated that radar can be used to survey the condition of not only overlaid decks but also decks that have their original surfaces. It also has shown that delaminations in a concrete deck are manifested as irregularities, or recognizable signatures, in recorded microwave reflection bands that result from reflections at the top mat of the reinforcing bars. Although the speed and accuracy of the technique need to be improved, as will be done through further study, it is usable as is for collecting information on the condition of decks that otherwise would be unattainable.

Faced with a severely reduced budget, bridge engineers now more than ever need reliable data from routine deck-condition surveys to aid them in the assignment of priorities and scheduling of maintenance on bridge decks. For surveying the extent of delaminations in concrete decks that have not been overlaid with bituminous concrete, infrared thermography  $(\underline{1},\underline{2})$  is proving to be a faster and more effective method than conventional sounding methods.

For overlaid bridge decks, the conventional sounding methods are even more 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 coring, partial removal of the overlay, or examinations of the undersides of decks. None of the procedures can provide a reliable estimate of the extent of repair needed on a concrete deck; therefore, the efficient budgeting of repair funds for overlaid decks is extremely difficult.

In recognition of the need for a rapid and nondestructive inspection technique for overlaid bridge decks, all potentially applicable techniques being used in various industries were investigated, and it was concluded that ground-penetrating radar (GPR) had the best potential. This assessment was given credence by a recent report on an ongoing effort that involved the experimental application of GPR for the evaluation of bridge decks (3).

This paper describes the principle of GPR and the experimental use of the technique in the inspection of concrete bridge decks. It also presents some observations made so far in a continuing developmental effort.

#### PRINCIPLE OF GPR

Ground-penetrating, or downward-looking, radar came into existence in the late 1960s. 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 ( $\underline{4}$ ), and its use for locating undermining of concrete sidewalks ( $\underline{5}$ ) and voids under concrete highways ( $\underline{6},\underline{7}$ ), and for determining the thickness of bituminous overlays ( $\underline{8}$ ), has recently been reported.

In practice, a radar apparatus that uses a transducer for both transmitting and receiving is used to transmit impulses of microwave frequency (900 MHz) into an overlaid concrete, as depicted in Figure 1. When these electromagnetic pulses strike the surface of the bituminous concrete, a portion of the pulse energy is reflected and the remainder penetrates the bituminous layer. The remaining pulse then strikes the bituminous concrete and portland cement concrete interface and again part of it is reflected. The portion not reflected penetrates the reinforced concrete slab and either strikes reinforcing bars and is reflected or penetrates through the slab.

When the concrete slab is delaminated, there is an additional reflection from the deteriorated area. The more severe the delamination, the more pronounced is the resulting reflection.

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 is recorded on an oscilloscope as a composite waveform that can be displayed on a facsimile graphic recorder as a depth (or reflection) 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 the composite waveform is characterized by the amplitude and time of flight of each reflected pulse. These parameters are, in turn, dependent on the nature of the reflecting interfaces and the materials involved.

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 that condition. It must be emphasized that the same argument can be made for bridge decks that have not been overlaid, and that GPR would be applicable to them also.

#### STUDY METHODOLOGY

#### Instrumentation

The pulse radar system used was manufactured by Geophysical Survey Systems, Inc., of Hudson, New Hampshire. It consisted of a model 4400 control unit, an EPC 2208 graphic recorder, a model 02 power distribution unit, and a model 101c transducer. The transducer (Figure 3), which provides a relatively narrow pulse of approximately 1.1 nanoseconds (ns), was selected to yield the best possible resolution, or separation, of the pulses reflected from the various interfaces in a nonoverlaid or overlaid concrete deck. This transducer radiates the microwave pulses in the shape of cones that extend 90° and 60° along its length and width, respectively.

For the field work in the research reported here, the system was carried in the back of a station wagon and was laid out as shown in Figure 3. Power was supplied by the 12-V car battery, with the car engine at idle, through the power distribution unit, which also supplied the 120 VAC needed for the recorder (Figure 4). Before a survey was performed, a model P460 calibrator was connected to the control unit in place of the transducer to provide 10-ns impulses for calibrating the time (or depth) scale on the graphic chart. To facilitate the interpretation of radar reflection profiles recorded for a deck, which is an important key to success in this use of GPR, and since radar reflection profiles for bridge decks have not been reported in the literature, there was a need for "ground truth" (calibration) data. Because these data were collected by conventional sounding methods, only overlaid bridge decks already scheduled for repair were included in the study, so that each deck surveyed by GPR could also be sounded for deteriorated concrete after the overlay was stripped.

Before a deck was surveyed with GPR, it was marked with a grid to facilitate the plotting of delaminated areas located by GPR and sounding in composite sketches (shown later in this paper). This was done for comparison purposes and in no way is it absolutely necessary in an operational use of GPR for surveying decks.

Figure 1. Transmission of radar pulses through delaminated bridge deck that has been overlaid.



Figure 2. Data presentation of GPR.

During a radar survey, a scan was made at every 2-ft interval across the width of a deck by manually towing the transducer, which sat above an appropriate dielectric spacer (to be discussed later), over and along the length of the deck to produce a reflection profile on the graphic recorder. The typical towing, or scan, speed was estimated to be approximately 20 ft/min.

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

During the scheduled repair of the overlaid deck, the delaminated concrete areas were located with the conventional dragging of chains, supplemented with hammering, immediately after the overlay was stripped from the deck.

In addition to overlaid bridge decks, two sizable old concrete deck slabs, each measuring slightly larger than 6xl2 ft and belonging to the Federal Highway Administration (FHWA), and portions of two decks that had their original concrete surfaces, were studied with GPR. The slabs, which were about 7 in thick, had been 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.

#### Use of Dielectric Spacers

Essential to the detection of concrete delaminations by GPR is the proper separation, in time on the re-

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SKETCH OF A SINGLE PULSE AND REFLECTIONS AS SEEN BY THE RECEIVER EXAMPLE OF PROFILE INFORMATION AS DISPLAYED BY THE GRAPHIC RECORDER corded reflection profile, of the electromagnetic pulse reflected from the deteriorated concrete from other reflected pulses and the transmitted pulse. Assuming that the typical thickness of concrete cover over the top mat of reinforcing steel where delaminations originate is less than 2.5 in and that the relative dielectric constant of concrete is approximately 6 [as suggested in the literature ( $\underline{6}$ )], the transit time of the pulse reflected from a delamination would be less than 1.0 ns according to the following equation:

$$t = 2D/V = (2D\sqrt{\epsilon})/C$$
(1)

where

- t = transit time, or elapsed time, between pulses reflected from the top and the bottom of the material (ns);
- D = thickness of material (ft);

Figure 3. Instrumentation for radar subsurface profiling.





Figure 4. Block diagram of pulse radar system.



This would result in the reflected pulse being at least partly overlapped, or masked, by the other pulses that arrive at the receiver unless a dielectric spacer was inserted between the transducer and the surface of the deck.

Ideally, a spacer should be of a material whose dielectric property is identical to that of the deck surface. For nonoverlaid decks, dry sand is convenient, since it is reported to have dielectric constants of 4 to 6  $(\underline{9})$ , which are close to that of concrete. Figure 5 shows how dry sand was used in surveying the original concrete deck surfaces and the slabs mentioned above.

For the survey of overlaid bridge decks, a block of bituminous concrete that measured approximately 8.5 in wide by 14.0 in long by 3.0 in high was used as the spacer.

#### DISCUSSION OF RESULTS

#### Concrete Slabs and Decks with Original Surfaces

Because no recording of a reflection profile for either a nonoverlaid or overlaid bridge deck had been reported in the literature, and it was not known how reflection features that correspond to concrete delaminations beneath an overlay would appear on a profile, it was decided to observe the profiles for the deteriorated original deck surfaces first. Therefore, the two concrete decks and two slabs were studied first, although the primary goal of the investigation was to develop a nondestructive technique for overlaid decks.

#### Concrete Deck Slabs

Figure 6 shows the condition of one of the FHWA deck

#### Figure 5. Sandbox used as dielectric spacer for concrete deck.



#### Figure 6. Condition of concrete deck slab.



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Spall Delamination slabs, labeled GL-2, as determined by visual inspection and sounding with chains and a hammer. The radar survey on this slab consisted of five linear scans made at 1-ft intervals along the length of the slab with the use of an 8-in sand spacer. The resulting set of five radar reflection profiles is shown in Figure 7. These profiles are guite similar to those recorded for the other deck slab studied.

In the interpretation of such reflection profiles, it is necessary to identify which reflection bands in each profile came from the top mat of reinforcing bars around which most concrete delaminations originate. This is done by first estimating the transit time for the radar pulses to travel from the transducer to the top mat of the reinforcing bars and back. Assuming that the average depth of cover of these bars was 2 in, the thickness of the sand spacer was 8 in, and the relative dielectric constants of both concrete and sand were 6, then the use of Equation 1 would yield a total transit time of approximately 4 ns.

Examining Figure 7, one can observe that, at approximately 4 ns (i.e., around the third and fourth bands), the reflection pattern assumed the shape of blips. These blips and other sharper ones, shown in profiles presented later, characterize reflections from the relatively small cross section of rebars and therefore would serve as a prompt indicator of such reflections.

After identifying the reflection bands from the rebars, the next step is to search for any irregularities along them. Looking first at scan line 1, one can see a distinctive depression from the 8- to ll-ft marks along these bands. This depression corresponds to the nearby large delaminated area, which was located by conventional sounding on the right side of the slab (Figure 6). In scan line 2, the same feature appeared from about the 8- to ll-ft 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 in about the 0.5- to 3.5-ft 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 most of the delaminated areas in these slabs were found to be located in the wheel paths.

In contrast to the waveform-type data reported recently elsewhere  $(\underline{3})$ , which require further processing (by computer, as suggested by the researchers) before being of practical value, the reflection profiles in Figure 7 and latter figures represent already processed data. As demonstrated in the above discussion, these reflection profiles bring forward concrete delamination in easily recognizable signatures, or irregularities, in the reflection bands for the top mat of rebars. At the risk of appearing to endorse an instrument, it should be emphasized that the profiles are not the consequence of the particular survey procedure used in this study but rather the convenient output of the fac-simile graphic recorder used.

#### Concrete Bridge Decks

The first concrete deck tested had delaminations in less than 10 percent of its entire three-span area as determined by conventional sounding. Two test areas were selected from two spans to include about 50 percent of the delaminations, as shown in Figure 8, 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 1 ft apart.

Figure 8 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 marks was detected by the transducer as it went over the area with the 4-in dielectric spacer on scan lines 1 through 4, as shown in Figure 9. The transducer began to "see" the other large



Figure 7. Reflection profiles for slab GL-2 obtained with 8-in sand dielectric spacer.

delamination, which is in the upper-right quadrant of the test area, in scan line 7. The neighboring smaller delamination was not noticed until scan line 9, and even then it was not 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.

As shown in Figure 8, 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 lines 1-4, which are presented in Figure 10, indicates that the transducer did not 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 current experimental setup is one about 1 ft 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 lines 6-9 in Figure 10. It is interesting to note that the delaminations located along scan line 5 appeared as blurs in the reflection profile. Last, the smaller delamination located between the 18- and 20-ft marks (Figure 8) showed up faintly in the profiles of scan lines 7 and 9.

A similar survey of a second concrete deck yielded practically similar observations, except that the radar reflection profiles for this deck, an example of which is shown in Figure 11, were noticeably different from those of the previous slabs and deck (Figures 7, 9, and 10).

In summary, the results for the concrete slabs and decks with original surfaces generally showed Reflection profiles from one deck can be noticeably different from those of another deck. The difference probably arose from such likely determining factors as differences in the concrete mixes, the thickness of concrete cover over the top mat of rebar, and the amount of reinforcement.

The transducer did not have difficulty in picking up relatively large delaminations; however, it was less consistent for delaminations about 1 ft across.

#### Overlaid Concrete Bridge Decks

GPR has already been used experimentally to survey several bridge decks of various lengths and designs, and for four of the decks subsequent surveys by conventional sounding were conducted after their overlays were removed for deck repairs. Similar soundings on the other decks will be made in the coming construction season.

#### Overlaid Deck 1

The radar reflection profile in Figure 12 is typical of those recorded for the first overlaid deck surveyed. The overlay was approximately 2 in thick. This profile shows that reflections from concrete delaminations also appeared in the shape of depressions, which by now are a familiar signature of delaminations. The relatively tiny and sharp spikes, or blips, that appeared in the fourth band and are regularly spaced at approximately 6 in are reflections from the top mat of rebars. Again, this feature aids the user in quickly identifying reflection bands that arise from the top mat of rebars where the delaminations originate.

In an actual application of this technique, the



user would go through profiles like that shown in Figure 12 and search out signatures, or irregularities, to locate the delaminations under the overlay. In a simulation of this process, suspected delaminations in the two study areas on this deck were located from the recorded reflection profiles and are shown in Figure 13 along with delaminations located by conventional sounding performed after the overlay was removed.

It is evident that there were some discrepan-

cies. As given in Table 1 where the results are categorized, some of the discrepancies involved the radar giving positive results in locations not judged to be delaminated by sounding, which can be classified as category 3. In most cases where this category of discrepancies occurred, cracks in the overlay were noted. However, the cracks cannot account for all these discrepancies, since cracks in other overlays have been observed to be manifested in reflection profiles as sharp, downward-pointing



Figure 9. Some reflection profiles for test area A in concrete deck 1.

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spikes, and the unaccounted for depressions, one of which is shown in Figure 12, were considerably wider.

The other discrepancies (category 2) involved the radar giving negative results where sounding indicated delaminations. It appeared that this type of discrepancy occurred where the delaminations were about 1 ft wide or less.

To provide a basis for gauging the performance of the radar, assume that conventional sounding gives perfect results, i.e., that it identifies all the delaminations in the test areas. Based on this as-

Figure 10	. Some re	flection profiles	for test area	B in concrete	deck 1.
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sumption, radar would appear to have an accuracy of 80 percent, as shown in Table 1. This means that radar missed about 20 percent of the delaminations in the test areas on this deck. However, since radar also located category 3 delaminations, the technique actually yielded a net overestimation of 17 percent for this deck. This last statistic is very useful to a bridge engineer who has decided to use radar results to estimate the amount of needed deck repair.

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Overlaid Decks 2, 3, and 4

Figures 14-19 show examples of reflection profiles for the remaining three overlaid decks, which already had been sounded with chains and a hammer, and their corresponding diagrams of radar and sounding results. As illustrated in Figure 14, overlaid deck 2 provided the most complicated reflection profiles recorded so far. This complexity resulted from the arching of the deck and the accumulated layers of overlay, which varied in thickness from 7 in at the middle of the deck to 14 in at the ends and were disbonded at places between overlays and between the



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first overlay and the concrete. Incidentally, a close examination of these profiles indicated that there was a very good linear correlation (correlation coefficient of 0.98) between the measured total thicknesses of the overlay and the pulse transit times through the overlay. This confirms that GPR can be used to nondestructively measure the thickness of an overlay on a bridge deck, as reported elsewhere ( $\underline{8}$ ).

on deck 2 as it did on the other decks. This relatively poor performance must have resulted from the above-mentioned unusualness of the deck and, consequently, the extremely complex reflection profiles. Excluding this unusual deck, the overall performance of the radar was uniformly good.

#### SUMMARY AND CONCLUSIONS

As Table 1 shows, radar did not perform as well The data collected so far in this continuing re-

Table 1. Analysis of GPR performance.

Figure 13. Test areas for overlaid deck 1.

Overlaid Deck No.	Linear Feet of Delamination Located by				
	Radar and Sounding, Category 1 (C1)	Sounding Only, Category 2 (C2)	Radar Only, Category 3 (C3)	Accuracy by Radar <sup>a</sup> (%)	Overesti- mation by Radar <sup>b</sup> (%)
1	120	30	55	80	17
2	250	145	130	63	-4
3	500	115	225	81	18
4	430	50	110	90	13

<sup>a</sup>Formula: (C1 x 100)/(C1 + C2). <sup>b</sup>Formula: [(C3 - C2) x 100]/(C1 + C2).

Figure 14. Microwave reflection profile for overlaid deck 2, arched reinforcedconcrete deck.

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search have shown that GPR can be used with reasonable reliability to nondestructively survey overlaid concrete decks. This is made possible by the manifestation of concrete delaminations as recognizable signatures or irregularities in the radar reflection bands from the top mat of rebars.

The reflection profiles may vary appreciably

among decks, depending on the nature of the deck and the condition of the overlay. Sometimes the distinction between reflection patterns for sound and deteriorated concrete is very fine, especially when the deterioration is small or shallow. Deteriorations on the surface of the concrete slab, which have resulted from freeze-thaw damage by moisture



Figure 16. Reflection profile for overlaid deck 3.







trapped between the overlay and the slab, currently are difficult to differentiate from concurrent overlay disbondment. (Perhaps in the application of the radar technique the user should assume the existence of surface deterioration of the concrete slab wherever disbondment of the overlay is indicated by the reflection profiles.) Wide cracks, about 0.25 in and wider, in the overlay may lead to false indications of delamination in the concrete.

In this study, the procedure and instruments were found to be easy to use, and if lane closure is not a problem, the procedure can be used as is to collect valuable information on the condition of decks for the assignment of maintenance priorities and for the estimation of needed repairs. The instrument was purchased off-the-shelf for about \$25 000. Without gridding a deck, the radar survey itself would take only approximately 2.5-3.0 h to perform on a deck 44 ft wide and 200 ft long and scanned at 2-ft intervals across its width and along its length. This would result in the radar scanning of approximately 4200 linear feet of the deck. The service of an engineer is not absolutely necessary, but the interpretation of the reflection profiles requires a skilled technician with some training in the task.

Future efforts will be directed at improving the speed of the survey to the extent, if possible, of eliminating the need for a complete lane closure.

In addition, more overlaid decks will be surveyed so that the various signatures of delaminations that have been encountered may be categorized according to their accuracy. This will lead to improved interpretations of the reflection profiles and, therefore, improved assessments of the condition of decks and the amount of repairs needed.

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#### Abridgment

## Bridge Rehabilitation Programming by Using Infrared Techniques

#### RITA E. KNORR, JOHN M. BUBA, AND GREGORY P. KOGUT

Techniques used to determine the needs and characteristics of bridge and roadway maintenance are highlighted. The results imply that the use of infrared equipment for inspections is appropriate to accomplish relatively rapid evaluations. However, limitations of the technology are apparent in observing overlaid surfaces because the distinction between delaminated areas versus debonded bituminous overlaid pavement areas was not reliable. Despite the deficiencies associated with performance as a precise testing mechanism, infrared thermography has an application as a tool to collect historical data and provide a basis for programming rehabilitation projects.

Several methods are used to describe the current condition and provide projections of future rehabilitation needs for the bridges on the Illinois tollway system. An annual inspection program that consists of a visual analysis of regular maintenance needs is supplemented with more detailed analysis each three or four years. There are more than 450 bridges (85 percent of which have been in service more than 20 years) that are included in the maintenance and rehabilitation program. Although the substructures are in good condition, there is an increasing need to have a more formalized approach to describe the bridge deck condition.

In 1976 the Illinois State Toll Highway Authority initiated a program to develop a more thorough method of bridge deck inspection, which included Delamtect surveys. Continuation of the program to set priorities for rehabilitation included the detailed evaluation of the application of infrared thermography.

#### PAST APPLICATIONS

The inspection program focused on bridge deck evaluation methods and isolated several of the available technologies in use to evaluate the deterioration, detection, and rehabilitation needs on the tollway system. The five techniques that have been studied include Delamtect, electric-potential readings, pulse-velocity measurements, swept-frequency radar, and thermal mapping. The study concluded that no single evaluation method was capable of describing the delaminated areas within a level of accuracy required for the preparation of contract documents. The most cost-effective diagnostic method for the short-term needs of the tollway was the Delamtect, even though the research team experienced numerous inconsistencies in the evaluation and plotting of Delamtect results (1).

Delamtect and other acoustical methods have been used to establish the condition of the reinforcedconcrete deck slab beneath the asphalt wearing surfaces on bridges that have not required extensive maintenance in the past and have experienced deck deterioration. However, Delamtect requires excessive time for lane closures, and there is considerable variability of the data obtained with different overlays, sealers, and environmental conditions. Due to these problems, the Illinois State Toll Highway Authority was interested in pursuing evaluations from infrared equipment.

#### METHODOLOGY

The infrared methods employed for scanning the bridge decks in this study varied, as they were based on equipment and technique changes from 1976 to 1982. The earlier inspections included aerial and van-mounted equipment for the survey work. The aerial shots had significant distortions due to atmospheric conditions, reflection from oil drippings, tire and other markings, and sand and debris on the deck. The van-mounted equipment provided simultaneous recordings of the infrared scan and a video of the actual surface appearance. The video record allowed for correlation and subsequent plots of the bridge deck. Despite the highly sophisticated nature of the equipment used for the analysis, the results did not provide the clarity that was desired, nor did they correlate with visual inspection data.

The more recent inspections that have provided sufficient data are from an elevation of 15-20 ft in a bucket truck. The height is required to ensure