Bridge Deck Condition Surveys Using Radar: Case Studies of 28 New England Decks

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Repair and replacement of deteriorated bridge decks represent a major expense to many state highway agencies. Current techniques for assessing deck condition have limited the effectiveness of efforts to program, order by priority, and estimate maintenance and rehabilitation (M&R) projects. A research program sponsored by 5 New England states led to the development of ground penetrating radar as a rapid and accurate means for deck deterioration assessment. The program involved surveys of 32 asphalt-overlaid decks in the region, 28 of which were studied during maintenance for deterioration quantities. Before maintenance, radar was collected on all of these decks and analyzed. Analysis techniques were developed to predict the concrete deterioration from the variations in the concrete dielectric constant as computed directly from the radar waveforms. The computation was used to predict overall deterioration for each deck and each major span. This prediction was then correlated with the actual deck deterioration determined when the asphalt overlay was removed, and the bare concrete was visually examined and chain-dragged. Correlations were carried out both at a detailed project level (100 percent coverage) with underside survey, and at a network level (30 percent coverage). The project-level correlation produced a good fit ($R^2 = 0.83$), with standard error of ±4.1 percent of the deck area. The network-level correlation produced a reasonable fit ($R^2 = 0.72$) with standard error of ±5 percent of the deck area. Both project and network survey methods have subsequently been implemented at highway speed, at costs comparable to traditional survey methods.

Repair and replacement of deteriorated bridge decks represent a major expense to many state highway agencies. During the life of a bridge, the deck is typically replaced once and repaired frequently. Bridge deck deterioration is primarily caused by two mechanisms: (a) Freeze-thaw damage to the concrete (punky concrete), and (b) corrosion-induced delamination resulting from infiltration of chlorides introduced by winter road salting operation or by a saline environment (see Figure 1).

One of the major problems with bridge deck deterioration is that its severity and extent are difficult to assess. The mechanisms of deterioration occur below the surface, and their manifestations are not readily seen in visual inspections. This difficulty is particularly true for overlaid decks, on which both delamination and freeze-thaw damage can occur without visual manifestations. Consequently, agencies are forced to program, order by priority, and budget the repair and replacement of many structures whose condition is virtually unknown. This situation has led to major surprises during construction, and to overruns and overrepairs.

Current techniques for condition assessment of overlaid bridge decks are slow, labor intensive, intrusive to traffic, and unproductive of accurate estimates of quantity of deteriorated concrete. These techniques, which include core sampling, corrosion (half-cell) potentials, and chloride ion measurements, are well documented (*1*). Corrosion potentials and chloride ion measurements infer corrosion, but do not address unseen freeze-thaw damage. A more reliable technique, the chain drag, does not work either with asphalt overlays or in heavy traffic conditions with high ambient noise.

In recognition of this problem, a group of five New England States (New Hampshire, Vermont, Maine, Rhode Island, and Massachusetts), under the New England Transportation Consortium (NETC), sponsored a program carried out by the Massachusetts Institute of Technology (M.I.T.) to investigate the potential of new technology for bridge decks. These states almost exclusively have asphalt overlays, so the problem of deck assessment is shared. The participants in this program reflected a growing concern over their ability to keep up with the bridge deck deterioration problem in the future. The major concern was not the badly deteriorated decks, because these decks already displayed obvious surface spalling or severe underside indications. Rather, the problem was with the decks in the grey zone, where there were limited visual indications, and the degree of deterioration could vary from 0 to 40 percent of the deck area. A large population of decks built in the Interstate construction period fall into this area of concern.

The specific objective of the NETC program was to investigate two new technologies for bridge deck assessment, ground penetrating radar and infrared thermography. The approach was to conduct radar and infrared surveys on a group of asphalt-overlaid decks that were scheduled for maintenance. During maintenance, the asphalt was removed and the concrete surface observed and chain-dragged to determine deterioration quantities for removal. These quantities were correlated with the predictions from the radar and infrared surveys. These field correlations were carried out on 28 decks in the New England area. The field study was complemented by theoretical studies (*2,3*) and by laboratory studies on deck slabs recovered from the field.

The results of this study led to the establishment of a radar-based technique that produced accurate correlations with observed deterioration. Results for infrared thermography were

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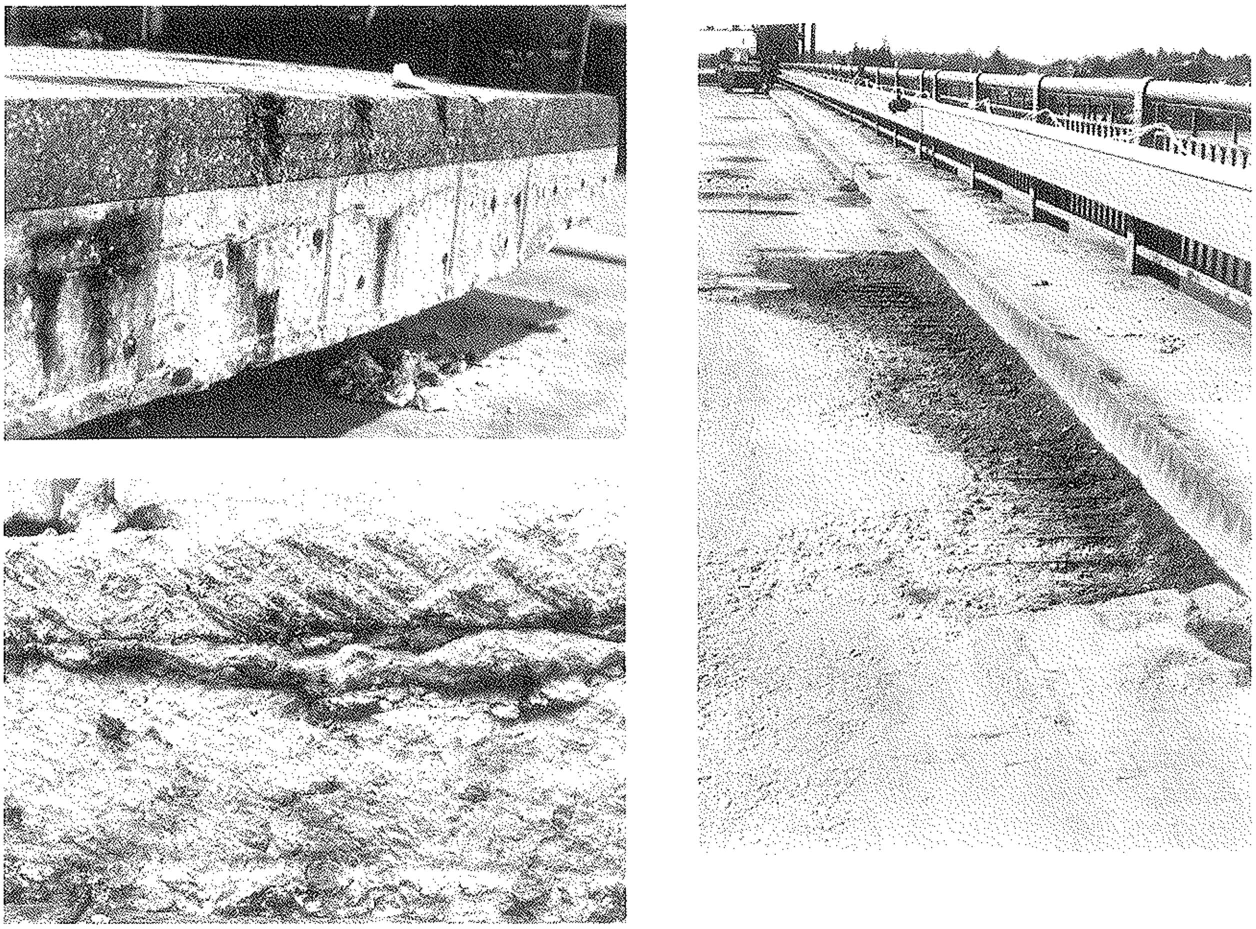
Infrasense, Inc., 19-R Brookline Street, Cambridge, Mass. 02139.



(a)

(b)

FIGURE 1 Bridge deck deterioration: (a) delamination, (b) punky concrete.

less favorable. The remainder of this paper will focus on the radar technology, and will include principles of radar for deck evaluation, deck site selection, survey procedures, data analysis, correlation with field observations, and current survey techniques that have evolved from this project. For the results of the infrared studies, the reader is referred to the project final report (*2*).

PRINCIPLES OF GROUND-PENETRATING RADAR

Ground-penetrating radar operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna attached to a survey vehicle (see Figure 2). These pulses are reflected back to the antenna with an arrival time and amplitude that are related to the location and nature of dielectric discontinuities in the material (air-asphalt or asphalt-concrete, reinforcing steel, etc). The reflected energy is captured and may be displayed on an oscilloscope to form a series of pulses that are referred to as the radar waveform. The waveform contains a record of the properties and thicknesses of the layers within the deck, as shown schematically in Figure 3. Figure 4 shows a typical set of bridge deck waveforms collected during the NETC project.

Bridge deck deterioration can be inferred from changes in the dielectric properties of the concrete (*3*). Concrete that has high moisture and chloride contents, as associated with corrosion damage and punky concrete, will produce a large reflection at the asphalt-concrete boundary (Reflection 2 in Figure 3). This reflection is caused by the higher dielectric permittivity produced by the moisture and chloride.

Figures 5 and 6 show the results of a numerical study of the sensitivity of the concrete reflectivity to moisture and chloride content. The study was carried out using electromagnetic models for predicting radar waveforms from concrete and asphalt material properties (*4*). The ratio, R2, is defined as the amplitude of the reflection from the top of the concrete normalized by the amplitude of the reflection from the top of the asphalt (*5*). The figures clearly show that both moisture and chloride content increase the reflectivity of the concrete.

Other indicators of concrete deterioration have been proposed in other investigations (*5–9*). These indicators, however, are all sensitive to the cross-sectional geometry of the deck, including asphalt thickness and rebar spacing and depth.

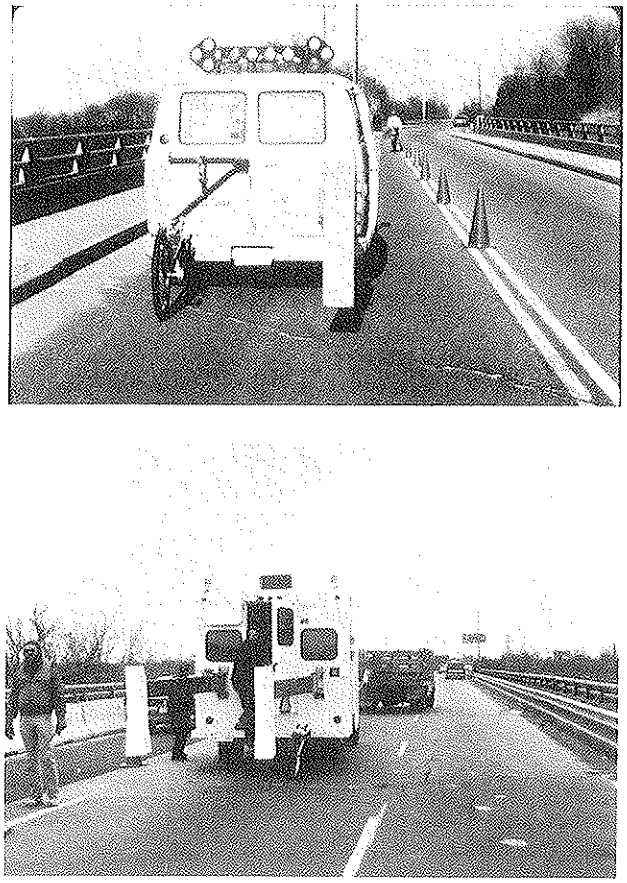


FIGURE 2 Radar data collection.

The geometric sensitivity of these indicators decreases their usefulness as indicators of deterioration, because geometry will vary within a deck and from deck to deck. The concrete reflectivity, however, is unaffected by cross-sectional geometry except when interference occurs because of thin asphalt (less than 2 in.) or shallow rebar cover (less than 1 in.). Under these circumstances, signal processing techniques are required to reveal the true value of the concrete reflectivity.

The deterioration determination is made by computing the concrete dielectric constant, ε_c, from the reflectivity, R2. This computation is based on the reflection coefficient between the asphalt and the concrete. The reflection coefficient between any two layers (1 and 2) is defined as the ratio of the amplitude of the incoming wave to the amplitude of the reflected wave. The reflection coefficient is related to the contrast in dielectric properties between the two layers, as follows:

$$\text{Reflection Coefficient}\,(1\text{–}2) = (\varepsilon_1^{1/2} - \varepsilon_2^{1/2})/(\varepsilon_1^{1/2} + \varepsilon_2^{1/2}) \qquad (1)$$

where ε is the dielectric constant, and Subscripts 1 and 2 refer to the successive layers. The dielectric constant of the asphalt can be determined at the air-asphalt interface by recognizing that the dielectric constant of air is 1. Using the reflection from a metal plate on the pavement surface to represent the incident wave (because the metal plate reflects 100 percent), Equation 1 can be rearranged to yield the asphalt dielectric constant, ε_a, as follows:

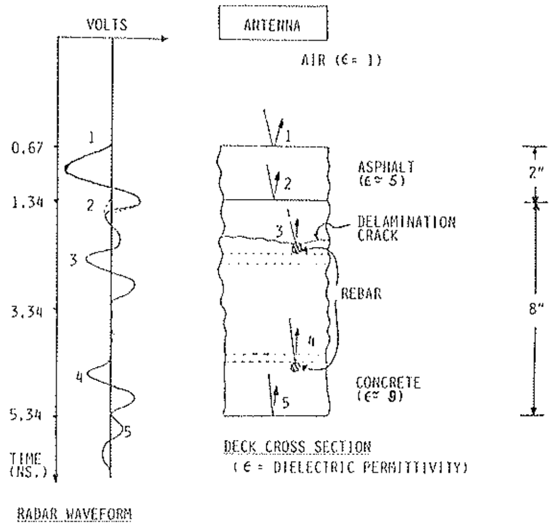


FIGURE 3 Radar bridge deck model.

$$\varepsilon_a = [(1 + A/A_{pl})/(1 - A/A_{pl})]^2 \qquad (2)$$

where

A = amplitude of reflection from asphalt (see Figures 3 and 4), and
A_{pl} = amplitude of reflection from metal plate (= negative of incident amplitude).

Equations 1 and 2 can now be combined with some additional manipulation to yield the dielectric constant of the concrete, ε_c, as follows:

$$\varepsilon_c = \varepsilon_a\,[(F - R2)/(F + R2)]^2 \qquad (3)$$

where

$$F = (4\varepsilon_a^{1/2})/(1 - \varepsilon_a)$$

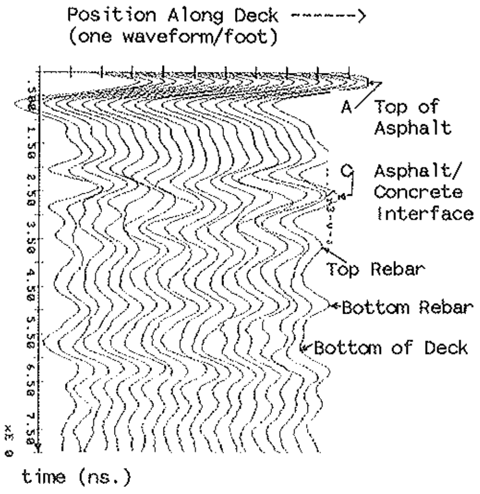


FIGURE 4 Typical waveforms.

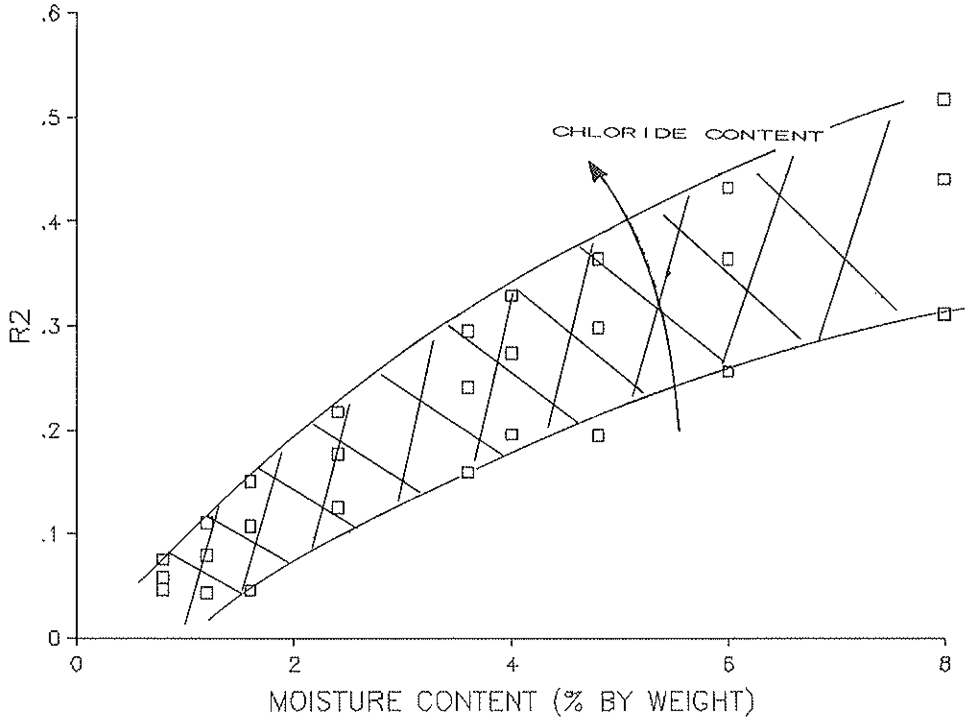


FIGURE 5 Concrete reflectivity (R2) versus moisture content.

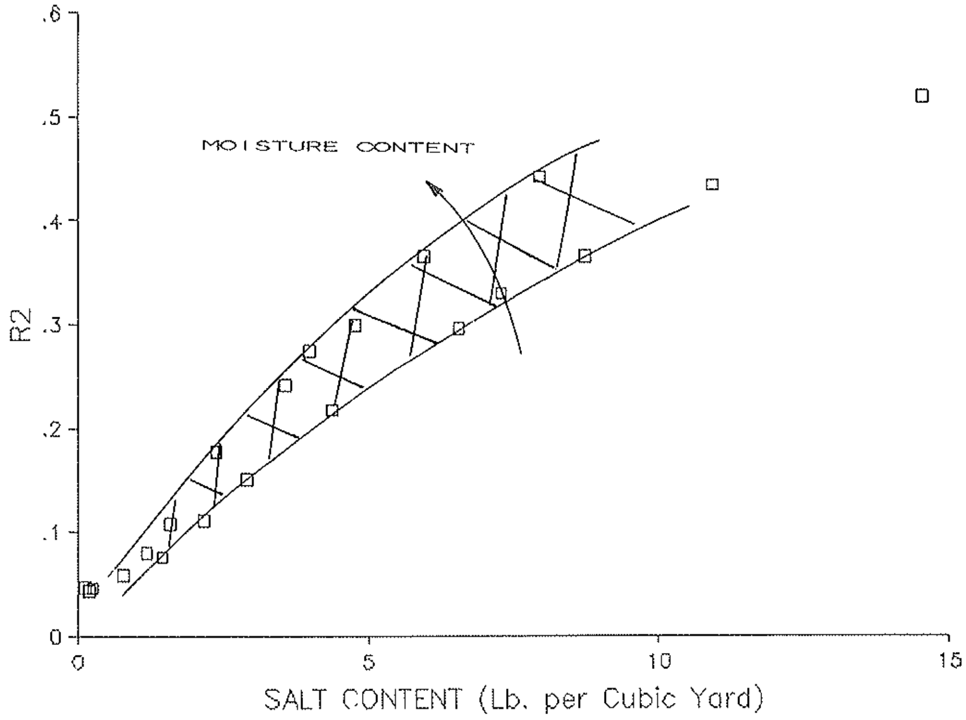


FIGURE 6 Concrete reflectivity (R2) versus chloride content.

The computed value of ε_c is used as an indicator of concrete deterioration. Normal concrete dielectric constant values range from 7.5 to 10.5, depending on air content, moisture content, and aggregate type. Deteriorated concrete has a higher value of dielectric constant. The quantity of deterioration is then inferred from the percentage of deck area exceeding a threshold value of dielectric constant.

Because the radar pulse has a width, the asphalt layer has to be sufficiently thick for the reflections from each layer to be clearly resolved. This minimum thickness can be calculated from the radar pulse width (in nanoseconds) and the radar velocity in the medium. For the horn antennas commonly in use for this application, this thickness is approximately 2 in. Ground-coupled antennas commonly used for geotechnical applications have transmit pulses that are two to three times longer because of ringing, and cannot resolve the concrete dielectric properties.

The analytical techniques described served as the basis for data analysis carried out during the NETC study.

DESIGN AND CONDUCT OF THE TEST PROGRAM

Identification of Deck Sites

Each participating state was asked to identify asphalt-overlaid bridge decks suitable for investigation during the research program. The selected decks were those that were scheduled for rehabilitation during the project period sometime after radar and infrared data could be collected. Deck rehabilitation involved asphalt removal, condition assessment of the concrete surface, and removal and repair of deteriorated concrete. Where possible, additional data describing deck condition were obtained either from previous inspections, or through planned testing during the rehabilitation process. These data included results of chloride content tests and corrosion potential measurements.

Collection of Radar Data

Radar data were collected initially by the M.I.T. and subsequently by commercial vendors. Radar data were collected over the entire deck by carrying out a series of longitudinal passes spaced transversely at 1.5 to 2 ft. This method allowed for 100 percent coverage of the deck. For the two antenna systems shown in Figure 2, with the antenna booms separated by 6 ft, this method was implemented as follows:

1. Position the van in the center of the lane;
2. Swing the antenna booms so that the right-side antenna is 2 ft from the curb, and the left-side antenna is 8 ft from the curb;
3. Acquire radar data with both antennas while they are traveling longitudinally down the deck at about 5 mph;
4. Return to the beginning of the deck, and swing the antennas laterally so that they are now at 4 and 10 ft from the curb, respectively;
5. Repeat longitudinal radar data collection;
6. Repeat the preceding process until the entire lane is surveyed; and
7. Repeat the preceding steps on the next lane.

For the single-antenna system, it was necessary to conduct twice the number of longitudinal passes, repositioning the van laterally for each pass and using a similar procedure to that just described. Traffic control was provided by state personnel to allow for the conduct of these surveys on in-service decks. In some cases, the decks were already closed with Jersey barriers in preparation for the planned repairs, and no additional traffic control was required.

Radar data were observed on an oscilloscope during the survey. Radar data were collected as continuous analog radar waveforms representing the reflections at the radar pulses off of the various interfaces within the bridge deck. These data were acquired for each continuous radar pass and stored on magnetic tape, along with fifth-wheel data that could be used to locate the radar data on the deck surface for subsequent processing and interpretation. (The use of analog tape has since been replaced by directly acquiring the data digitally using a data acquisition system on a personal computer).

Underside Surveys

Underside surveys were carried out both by state and M.I.T. personnel. General guidelines were established on what types of conditions to highlight in the underside survey. These included areas with rust stains, efflorescence, discoloration, and nonuniform dampness. Examples of these conditions are shown in Figure 7.

The underside survey was carried out by using the underside framing (girders and diaphragms) as a rectangular grid. With this grid, it was relatively easy to locate areas of interest within a particular rectangle. Surveys conducted both by state and M.I.T. personnel found a great deal of consistency in the location of areas of interest.

Chloride and Corrosion Potential Measurements

Chloride content measurements were made by M.I.T. project personnel and combined with data previously collected by state personnel and consultants. The numbers of chloride samples per span generally ranged from 3 to 10. Corrosion potential data were obtained either as corrosion potential values at selected locations or as a complete corrosion potential survey on a 5-ft grid. All of the corrosion potential data collected during this project were obtained from measurements directly on the bare concrete.

Chain-Drag and Material Removal Surveys

After the asphalt was removed, the concrete deck was normally chain-dragged to identify delaminated areas. The delaminated areas were marked with spray paint, as were areas in which concrete deterioration could be directly observed from the surface. Figure 6 shows a chain-drag survey in progress. Normally, the chain-drag survey was carried out by the

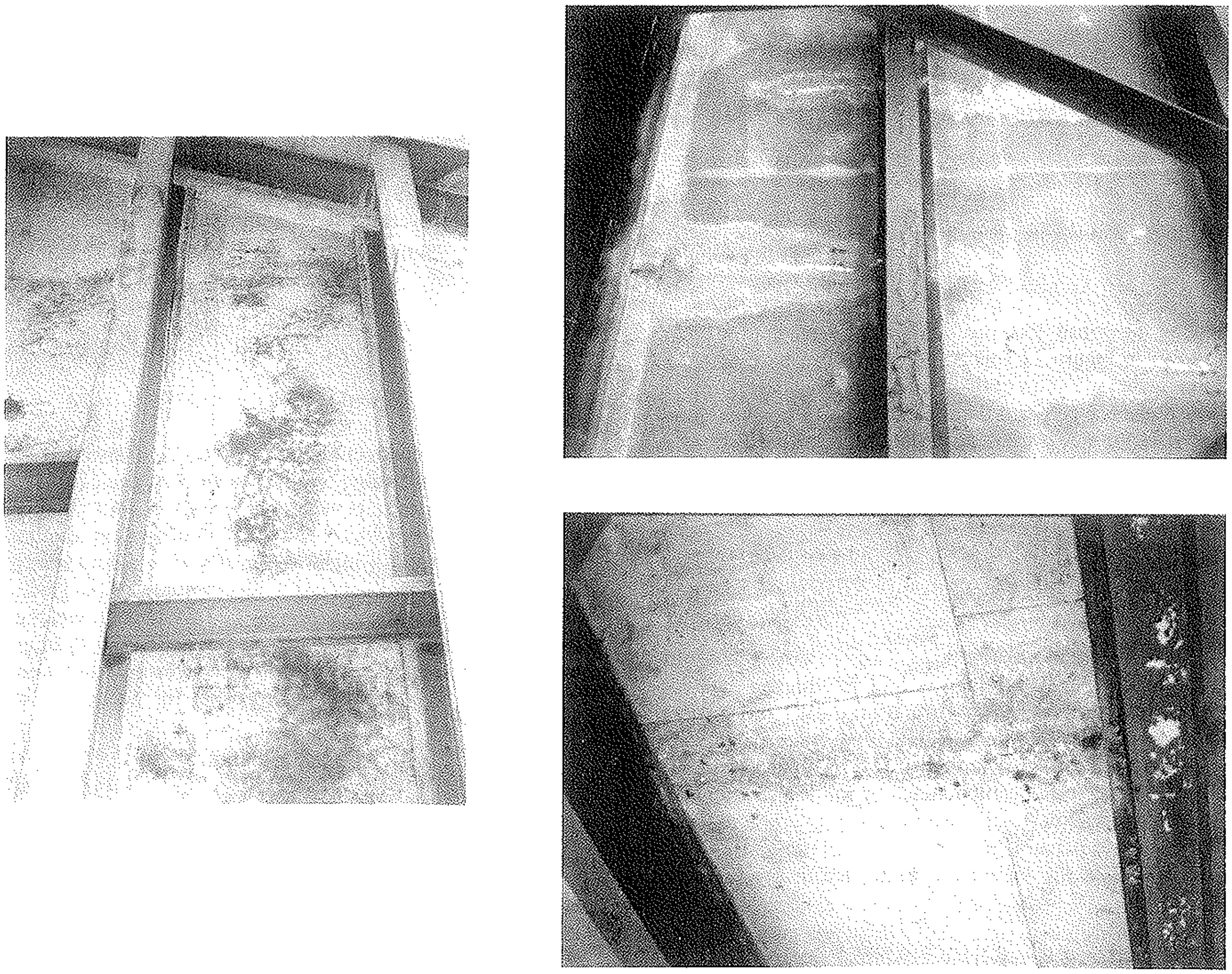


FIGURE 7 Examples of conditions noted in underside surveys.

resident engineer at the construction site, or by personnel from the state's materials or testing division. The results of this survey were then used by the contractor to identify areas where concrete was to be removed and replaced.

Maps of material removal were also obtained along with the chain-drag and surface deterioration surveys. The similarity between these maps depended on the contractor and on the state policy. In some cases, where the contractor followed exactly the outline of the chain-drag survey marks, they were identical. In other cases, the material removal was significantly greater than the marked deterioration because of squaring off and removal of additional concrete until corrosion was no longer seen.

DATA ANALYSIS

Data Entry

All of the data collected were directly transmitted to M.I.T. and entered into a computer data base for further analysis. The tape-recorded analog radar data were digitized using an analog-digital converter card installed in a personal computer. The radar equipment generated 50 waveforms per second. At the slow survey speeds used in this study, this ability resulted in many more waveforms than necessary for analysis. Therefore, the data were subsampled so that one waveform was digitized per longitudinal foot of travel. The digitized waveforms consisted of 500 points, representing 10 nsec of data.

The underside, chain-drag, and material removal data maps were digitized to scale using a digitizing tablet and AUTOCAD.

Computation of Deterioration from Radar Data

The method for radar data analysis discussed earlier was applied to the data collected as described. Deterioration predictions were programmed to be carried out automatically using numerical computations on the digitized waveforms. Typical output of the computer analysis is shown in Figure 8. This figure shows a plot of concrete dielectric constant versus longitudinal distance along the bridge deck for a single radar pass. The dielectric constant values for multiple radar passes

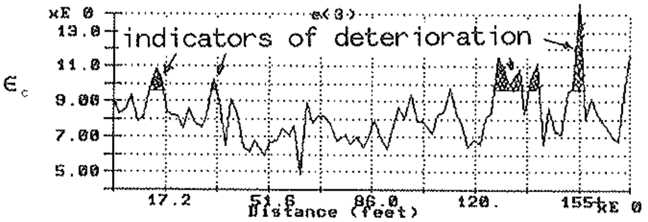


FIGURE 8 **Plot of computed dielectric constant versus distance.**

covering the entire deck can be displayed as a contour plot, as shown in Figure 9. This contour map can be used as an approximate indication of the locations of deck deterioration.

The dielectric constant data for all radar passes were used as a basis for the overall deck deterioration prediction. A number of alternative means for deterioration quantity estimations were investigated on the basis of these data, as described in the following section.

Data Interpretation

The analysis method was investigated using a variety of regression techniques to determine the best fit with the data collected on the 28 bridge decks surveyed during this project. The regressions considered a number of options, including use of radar data alone, spatial overlays of radar and underside maps, and linear combinations of radar and underside data. The regression studies also considered variations in the radar threshold percentage.

The results of the regression studies led to the following relationship.

$$\text{Deterioration} = \text{K1} + \text{K2}(U) + \text{K3}(R_N) \qquad (4)$$

where Kn are constants of regression, U is the percentage of deck area noted in the underside survey, and R_N is the percentage of deck area determined in Step 5 of the method using a threshold of N percent above the mean. This equation fit 26 bridge decks with an R^2 value of 0.83 and a standard error of 4.07 percent of the total deck area. The results of this analysis are presented in Table 1 and Figure 9. The two decks that were not included in this regression were identified as having asphalt thicknesses significantly thinner than 2 in., and thus not suited to the analysis implemented in this study.

APPLICATION OF RESULTS

The results have led to the introduction of a technique for assessing the deterioration in overlaid decks that is far more accurate than any other currently available method. On the basis of the results of this study, surveys are now being implemented with radar equipment operating at highway speed. Surveys are being conducted at various levels of detail. Project-level surveys seek 100 percent coverage of the deck area and include the results of an underside survey. These results provide sufficient detail for budgeting and scoping repair and rehabilitation projects. Network-level surveys seek 30 percent coverage of deck area, and do not necessarily include the underside survey. These results provide sufficient accuracy for network-level planning and for project priority setting.

Radar surveys can be carried out under all environmental conditions except for rain and subfreezing temperatures, and can be carried out day or night. Rain that produces standing water on the pavement surface distorts the dielectric constant computation and affects the deterioration prediction. Subfreezing temperatures alter the dielectric properties of the concrete in a manner that may obscure the detection of deterioration.

The following paragraphs describe current project- and network-level applications in further detail.

Surveys at Highway Speed

The possibility of conducting surveys at highway speed arose because the radar equipment generated 50 waveforms per second, enough data to provide one waveform per foot at 35 mph. The question that has been raised in the past is whether or not the results of a highway-speed survey would match those of a slow-speed survey. A recent study of pavement layer evaluation using radar (*10*) clarified this issue by yielding identical results for surveys conducted at 5, 15, and 40 mph. The data analysis techniques used in that pavement study were identical to those presented in this paper for application to bridge decks.

The province of Alberta, Canada, has recently conducted a pilot test of overlaid deck surveys conducted at highway speed. The surveys were conducted by Infrasense, Inc., of Cambridge, Massachusetts. The survey vehicle made continuous round trips at normal driving speed, crossing the decks at different transverse positions until complete coverage was achieved. Two or more decks in the same vicinity were covered in the same round trip. The radar survey vehicle was followed by a chaser vehicle during the survey, and no traffic control or lane closures were required. Data acquisition began before and ended after each bridge was crossed. The bridge deck data were isolated from the pavement data subsequently during office processing.

The surveys carried out as described were provided at a cost of approximately \$0.10/ft^2 of deck area. The decks were distributed throughout the province, with 3 in Edmonton, 14 along Highway 2 near Red Deer, and 7 in Calgary. Costs for other surveys could be more or less, depending on the relative locations of the decks and the logistics of the survey.

Network Level Surveys

The discussion has focused on developing a technique that provided a detailed condition assessment for decks that were being priority ordered and programmed for maintenance. There was also considerable interest among the New England states in developing a data base that included input of deck condition data for all decks in the state. Such a data base would represent an essential element of a bridge management system. The highway speed survey capability discussed could be exploited for this network-level application.

In this scenario, each lane of each surveyed deck would be covered by only two passes. In order to test out this network

TABLE 1 COMPARISON OF RADAR PREDICTIONS TO ACTUAL DETERIORATION (PERCENT OF DECK AREA)

Decks	Radar Prediction	Actual Deterioration	Error
Vermont			
#1	10	11	1
#2	12	9	3
#3	14	11	3
#4	21	12	9
#5	6	7	1
#6	6	7	1
#7	6	4	2
#8	6	12	6
#9	15	12	3
#10	5	3	2
Maine			
#1	16	20	4
#2	10	5	5
#3	6	4	2
#4	10	15	5
#5	11	5	6
Rhode Island			
#1	28	34	8
#2	38	40	2
#3	7	8	1
#4	7	5	2
#5	3	7	4
#6	2	2	0
#7	2	4	2
#8	5	3	2
New Hampshire			
#1	18	20	2
#2	2	0	2
Massachusetts			
#1	4	9	5
	AVERAGE ERROR		3%

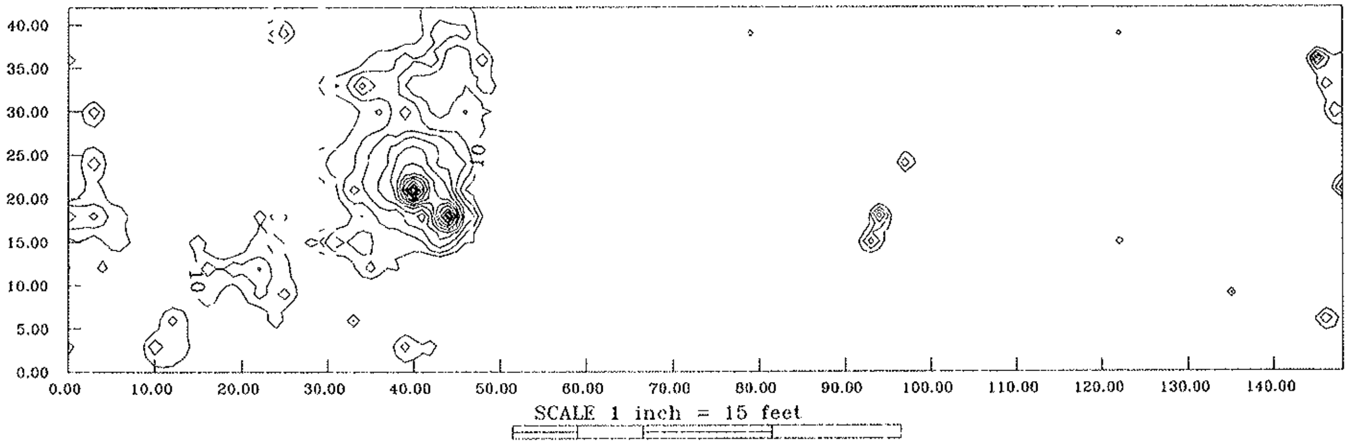


FIGURE 9 Surface contour plot of concrete dielectric constant, Abbott Bridge, westbound.

concept, the radar data collected during the NETC research program was analyzed as if it had been collected in the manner described for a high-speed network survey. For each lane of each surveyed deck, two passes, located approximately in the wheelpaths, were selected for analysis. The analysis used all the procedures described earlier, but treated the radar as the only source of information.

A linear regression model was developed for this data as follows:

$$\text{Deterioration} = K1 + K2(NR) \qquad (5)$$

where NR represents the radar deterioration estimate from the two passes per lane. Equation 5 was fitted to the data from the same 26 decks discussed earlier, yielding $R^2 = 0.72$, $S_e = 5.0$, $K1 = 0.61$, and $K2 = 2.04$. This result indicated that with only two passes per lane, the radar results correlated reasonably well with observed deterioration. The fit was not as good as that for the more detailed survey, but the results were accurate enough for network planning and priority setting.

On the basis of this these results, the New Hampshire Department of Transportation conducted a pilot program to evaluate the network survey concept. In a network-level survey, one envisions a radar van traveling continuously along the highway logging data for every bridge deck that it crosses. For a given round trip, the van would make one pass on each lane. With such a procedure, 20 to 40 decks could be surveyed in a day, a rate that would allow for complete coverage of a typical state bridge inventory in 50 to 300 working days. In addition, the automated nature of the radar processing would allow relatively efficient analysis of this quantity of data.

Results from the New Hampshire project have demonstrated the feasibility of conducting the network surveys. In two pilot network surveys, 24 decks were covered in 1 day and 9 in another day. Decks that were scheduled for repair were investigated to correlate radar predictions with the deterioration directly observed after asphalt removal. The radar predictions were consistent with these observations.

CONCLUSIONS

This work was motivated by a need to obtain more accurate information regarding the condition of bridge decks. The information was needed: to plan and budget overall maintenance, repair, and rehabilitation programs; to order maintenance and repair projects by priority; to select the optimum maintenance and rehabilitation approach, and to make repair and replace decisions; and to properly scope and budget maintenance and repair projects. Some of these needs require detailed estimates of amounts of deck deterioration, whereas others require reasonable estimates with less precision.

On the basis of the research described herein, a new method has been developed that accurately fits deterioration of overlaid bridge decks using processed radar data regressed against known deterioration from 26 decks. An additional outcome of this work has been the development of a high-speed deck survey concept applicable both to detailed project- and to network-level surveys. The detailed survey concept involves 100 percent radar coverage of the deck, and incorporates the results of an underside survey. The network concept involves one radar pass per wheelpath (30 percent coverage). Results for such a survey method have been simulated from the detailed data collected during this program. They have been shown to compare reasonably well with observed deterioration, but with less detail than in the detailed survey method.

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