Delamination and concrete quality assessment of concrete bridge decks using a fully autonomous RABIT platform

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Abstract. One of the main causes of a limited use of nondestructive evaluation (NDE) technologies in bridge deck assessment is the speed of data collection and analysis. The paper describes development and implementation of the RABIT (Robotics Assisted Bridge Inspection Tool) for data collection using multiple NDE technologies. The system is designed to characterize three most common deterioration types in concrete bridge decks: rebar corrosion, delamination, and concrete degradation. It implements four NDE technologies: electrical resistivity (ER), impact echo (IE), ground-penetrating radar (GPR), and ultrasonic surface waves (USW) method. The technologies are used in a complementary way to enhance the interpretation. In addition, the system utilizes advanced vision to complement traditional visual inspection. Finally, the RABIT collects data at a significantly higher speed than it is done using traditional NDE equipment. The robotic system is complemented by an advanced data interpretation. The associated platform for the enhanced interpretation of condition assessment in concrete bridge decks utilizes data integration, fusion, and deterioration and defect visualization. This paper concentrates on the validation and field implementation of two NDE technologies. The first one is IE used in the delamination detection and characterization, while the second one is the USW method used in the assessment of concrete quality. The validation of performance of the two methods was conducted on a 9 m long and 3.6 m wide fabricated bridge structure with numerous artificial defects embedded in the deck

Keywords: concrete; bridge decks; delamination; modulus; NDT; impact echo; surface wave testing; robotics; automation

1. Introduction

Concrete bridge decks deteriorate faster than other bridge components. The primary reason is their direct exposure to traffic and environmental loads, and consequently to maintenance

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procedures, like salt spreading in winter months. In addition, the inspection practices of the most State Departments of Transportation (DOTs) in the United States, and other bridge owners, detect problems only once those have reached their last stage of progression. Because of the mentioned reasons, State DOTs are using between 50 and 80 percent of their budgets for maintenance, rehabilitation, and replacement of bridges on concrete bridge decks.

The performance of concrete bridge decks was identified as the most important bridge performance issue by the Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program. To create knowledge about the performance of bridge decks, it is envisioned that hundreds of bridges will be evaluated and monitored in the next phase of the LTBP Program. To make this challenging task feasible, the FHWA initiated in 2011 the development of a robotic system for NDE of concrete bridge decks named RABIT (Robotics Assisted Bridge Inspection Tool). The main goal of the development was to improve both the speed and automation of data collection and data analysis components.

The following sections describe RABIT's components, operation and typical results. The specific objective of the paper is to describe the use of acoustic methods implemented in RABIT in concrete quality and delamination assessment, and present results related to the validation of their performance.

2. Deck Inspection using rabit

Effective bridge management requires strategies in the assessment of bridge decks that would enable capturing deterioration at all stages of its development. This can be achieved, among others, by a proper selection and implementation of NDE technologies. The most common types of bridge deck deterioration include corrosion, delamination, vertical cracking and overall concrete quality degradation. For example, in cases where deterioration is primarily caused by corrosion, the process can be described as the one initiated by the development of corrosive environment (Papadakis 2013). One of the ways to detect and characterize corrosive environment is by electrical resistivity (ER) measurements (Whiting and Nagi, 2003), and to some extent by ground penetrating radar (GPR) surveys (White 2014). As the corrosive environment becomes more severe, it will initiate corrosion activity in rebars. Furthermore, rebar corrosion will cause micro and macro cracking of concrete. These changes will be reflected through reduction of concrete elastic properties, which can be measured using the ultrasonic surface waves (USW) method (Nazarian *et al.*, 1993). As the deterioration progresses, it is manifested in deck delamination, which can be detected and characterized using impact echo (IE) (Sansalone *et al.* 1993), and often by GPR. Bridge decks with cementitious overlays, like Latex modified concrete (LMC), can be surveyed. However, for bridge decks with asphalt overlays, ER cannot provide meaningful results, and IE and USW measurements should be conducted at temperatures below 10 degrees Celsius.

2.1 Description of RABIT components

The RABIT system utilizes four NDE technologies: IE., USW, ER and GPR, and high resolution imaging of the deck surface and test point surrounding to inspect bridge decks. The main RABIT components on the front end are shown in Fig. 1. There are two acoustic arrays. Each of the arrays has multiple sources and receivers that enable multiple IE and USW testing, as will be discussed and illustrated later. The manual NDE technology equivalents for IE and USW testing

are shown at the bottom of the figure. The arrays are pneumatically lowered to couple the sources and receivers to the deck surface. The total width of the two arrays is 1.8 m, which matches the scanning width of the system. It is also equivalent to the half width of a typical lane.

RABIT's acoustic arrays, with their large number of sources and receivers and the arrangement of the two, can be considered to be equivalent to fourteen IE and eight or more USW devices. This is illustrated in Fig. 2. This enables surveys at a much higher spatial resolution than it is commonly used in deck testing using manual devices. It can be described that IE testing is conducted with a 15 cm resolution, and USW with a 30 cm resolution in the deck's transverse direction. Corrosive environment is assessed by four Proceq Resipod electrical resistivity (Wenner) probes attached on the front side of the acoustic arrays, as shown in Fig. 1. To establish electrical contacts between the deck surface and probes, the probes' electrodes are being continuously moistened using a fine spraying system. Finally, there are two high resolution cameras on the front end that are being used to capture the deck surface for mapping of cracks, spalls, previous repairs and other surface anomalies. The images that are being taken every 60 cm are later stitched into one or more large high resolution images of the deck surface.
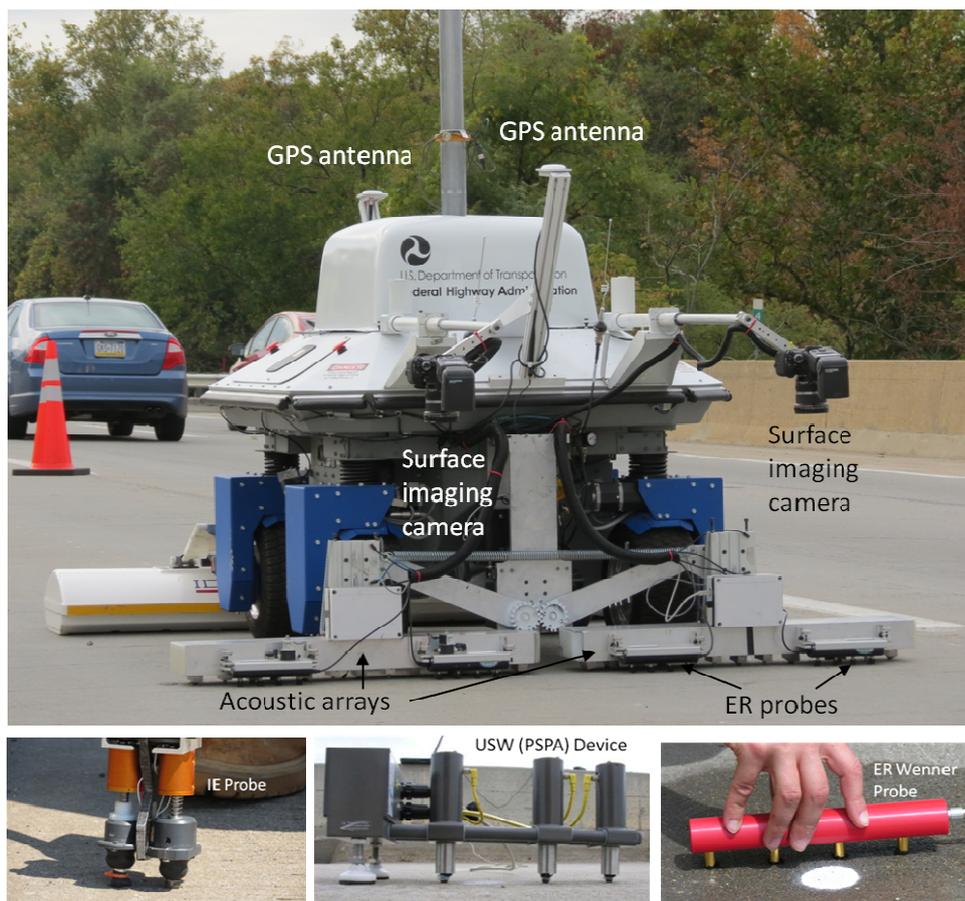
Fig. 1 Front end of RABIT with acoustic arrays, resistivity probes and digital cameras
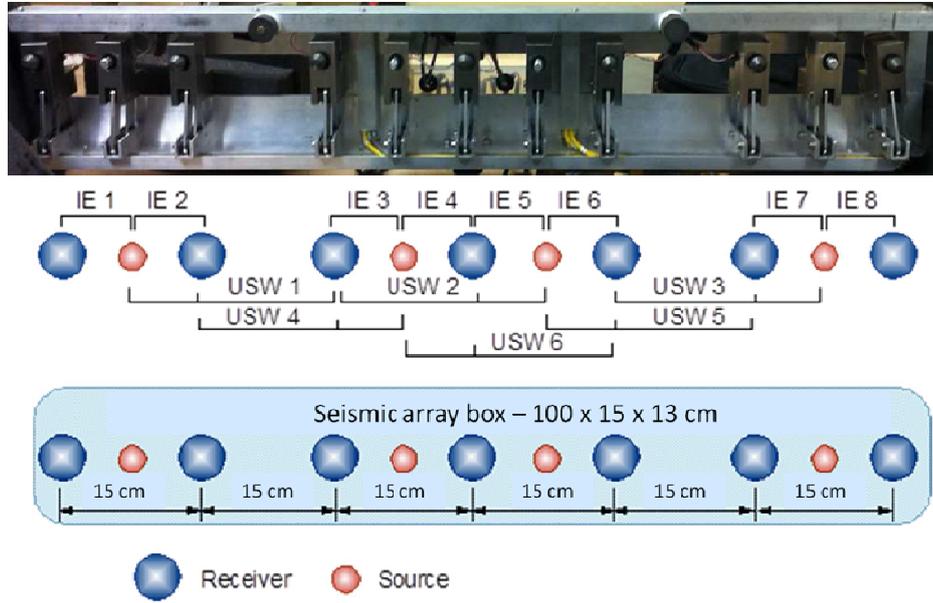
Fig. 2 View of the bottom side of an acoustic array and description of sensor and receiver usage

Fig. 3 Back side of RABIT with two GPR arrays and mast with a panoramic camera

The back side view of RABIT is shown in Fig. 3. Two IDS Hi-Bright GPR arrays are attached on the rear side of the deployment mechanism. Each of the arrays has sixteen GPR antennas, or eight pairs antennas of dual polarization. For a comparison, a manual single GPR antenna is shown at the bottom right corner. Also, the panoramic camera placed on a pneumatic mast in the middle of the robot can be observed in the figure. The mast can lift the camera up to 4.5 m for imaging of wider bridge deck areas.

2.2 RABIT navigation and data collection

The RABIT is conducting data collection fully autonomously. To navigate autonomously, the RABIT uses three devices. The primary navigation system is a differential GPS. The robot uses two Novatel antennas mounted on the robot, as shown in Fig. 1, and the third, the base station, mounted on a tripod typically on one end of the bridge. In addition, RABIT has an on-board inertial measurement unit (IMU) and a wheel encoder. The information from the three systems is fused using a Kalman filter to facilitate movement with an accuracy on the order of 5 cm order for the most of scanning. The survey starts with taking of the GPS coordinates of the GPS base station. This needs to be done only once for a particular bridge. Afterwards, the data collection path can be fully defined by taking GPS coordinates at three arbitrarily selected points on the bridge deck.
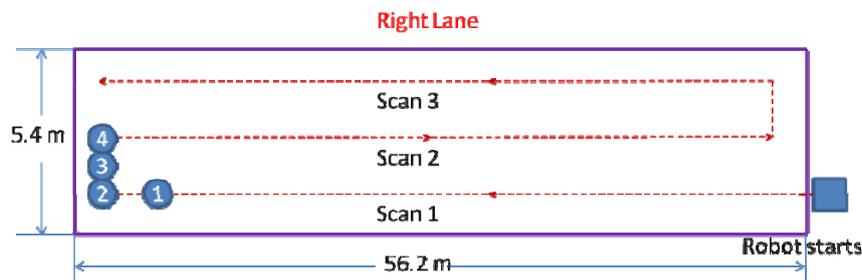
Fig. 4 Sample path planning and RABIT movement during surveys
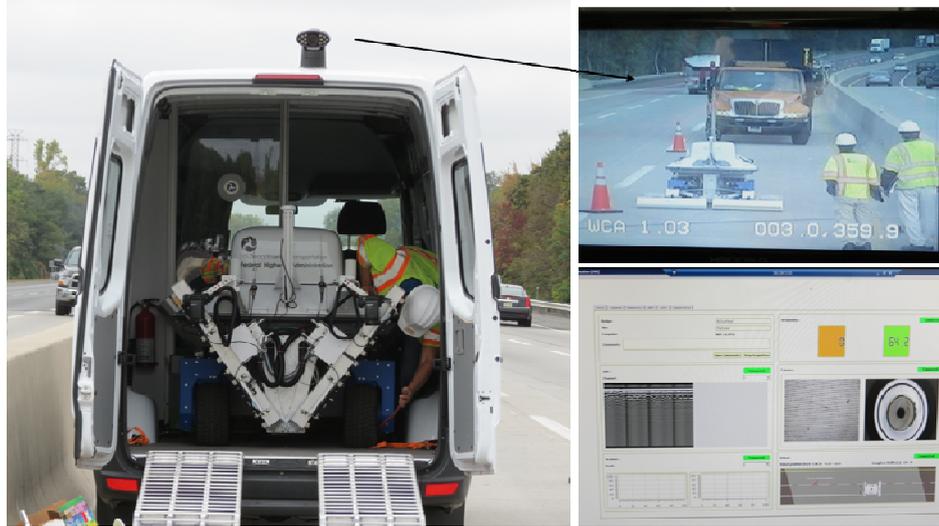
Fig. 5 Command van, and data collection and robot monitoring displays

The surveys are conducted by multiple 1.8 m wide sweeps of the RABIT in the longitudinal bridge direction, as illustrated in Fig. 4. The robot moves and stops at prescribed increments, typically 30 to 60 cm, and deploys the sensor arrays to collect the data. At the end of a strip, the robot first rotates in place 180 and degrees and move sideways across the bridge to the next scanning strip position before proceeding with another sweep. This process is also illustrated in Fig. 4. This type of maneuvering can be accomplished due to the four omni-directional wheels that allow the robot to move laterally and to turn at a zero radius. RABIT can collect data on approximately 300 m^2 of a bridge deck area per hour.

All the data from the sensor arrays and probes, and digital cameras are wirelessly transmitted to the "command van" shown in Fig. 5. The "command van" serves two main purposes. The first purpose is RABIT transportation. The RABIT is transported with the acoustic and GPR arrays folded, as shown in the figure. The robot loading and unloading is done using two ramps and manual control of the robot using a keyboard or joystick. The second, and more important purpose of the command van is to provide monitoring of all robot operations during the data collection and analysis. Four main displays are used for that purpose, as well as for the display in real or near real time construction of condition maps for some of the NDE technologies, calculates condition indices (Gucunski *et al.* 2012) and creates stitched deck surface images. In addition, two smaller displays enable monitoring of the robot movement and survey progression.

3. Acoustic array validation study

3.1 Preparation of concrete bridge deck in laboratory

A validation bridge structure was built on one of the campuses of Rutgers University to assist in research activities related to the development of automated non-destructive evaluation techniques

for concrete bridge decks. The bridge consists of a concrete deck and three supporting steel beams with steel bracing. The bridge is supported by two concrete abutments, as shown in Figs. 6 and 7. The concrete deck is 9 m long, 3.6 m wide (30 ft by 12 ft), and 203 mm (8 in.) thick. Therefore, it is large enough to simulate an actual reinforced concrete bridge deck. The concrete deck was built with two mats of uncoated reinforcing steel at 50 mm (2 in.) and 165 mm (6.5 in.) depths, respectively. Each of the reinforcing mats consists of 13 mm (#4) steel bars spaced at 165 mm (6.5 in.) in the longitudinal direction and 16 mm (#5) steel bars spaced at 177 mm (7 in.) in the transverse direction. The concrete mixture was designed to have a minimum 28-day compressive strength of 34.37 MPa (5000 psi), and the average 28-day compressive strength tested according to ASTM C39 was 64.53 MPa (9360 psi). The P-wave velocity measured by a direct method described in ASTM C1383 was 4530 m/s. The top surface of the slab was lightly broom finished for a rough surface, and water cured for 7 days after casting. The reinforcing steel used in the validation slab was grade 60 according to AASHTO M31.
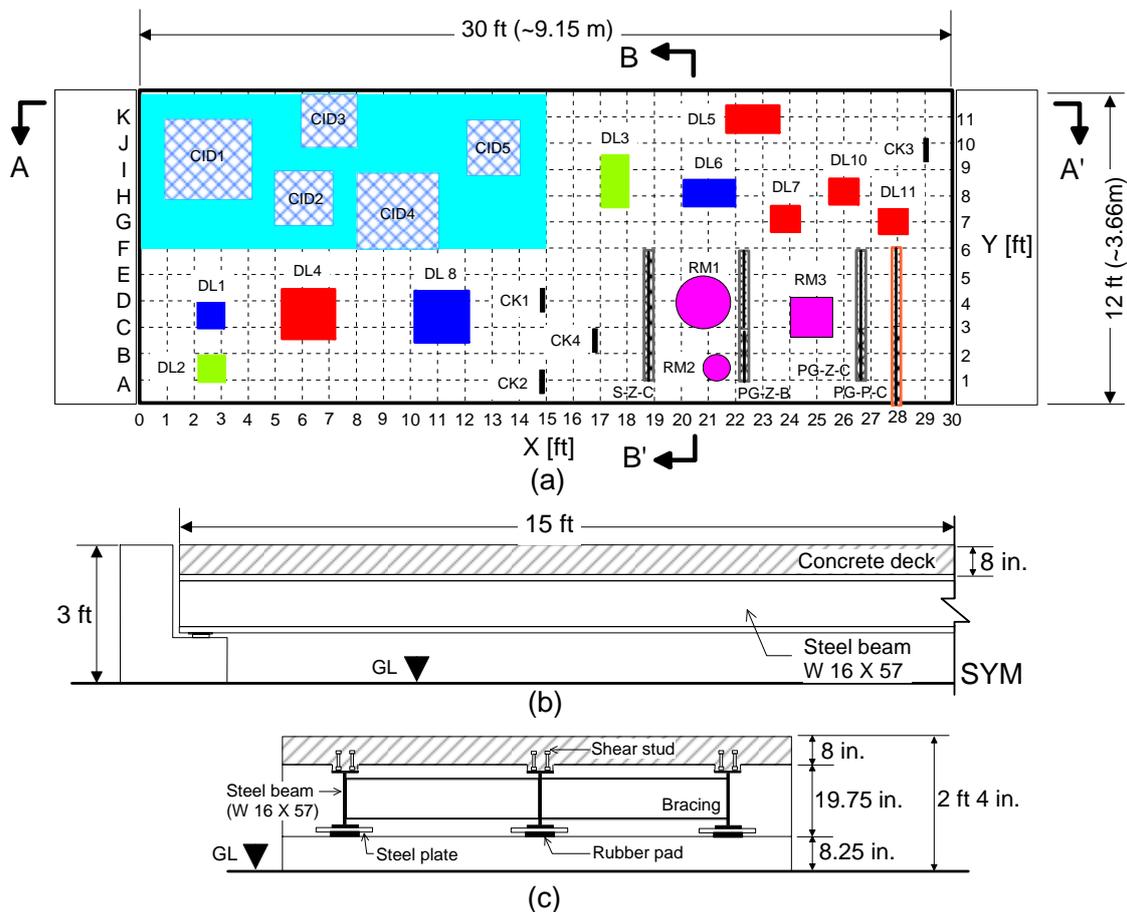
Fig. 6 Reinforced concrete validation bridge deck: (a) plan view of the specimen showing location of defects, (b) section view of A-A of the specimen, and (c) section view of B-B of the specimen. (Note: the locations of defects shown do not represent actual locations.)

Fig. 7 NDE validation bridge structure

The simulated concrete deck was designed to contain four different types of artificial defects: delaminations having various depths and areal extent (DL), surface-breaking cracks having various depths (CK), deteriorated regions with reduced elastic modulus (RM), and four cable conduits (three of zinc and one of plastic) including steel strands with different grouting conditions (see Fig. 6). The delaminations were fabricated by using two layers of plastic foam pieces covered by thin plastic film with various sizes and at three different depths. Shallow delaminations was placed at a 5 cm (2 in.) depth, intermediate delaminations at a 10 cm (4 in.) depth, and deep delaminations at a 17 cm (6.5 in.) depth. To insure that the delaminations are positioned at the designed depth, the thickness of the slab was divided into four layers (a layer including the bottom reinforcing steel, middle of the slab, a layer including the top reinforcing steel, and the top surface of the slab), and concrete was casted layer by layer. Surface-breaking cracks were built in the deck by inserting a layer of plastic sheets before concrete casting. The design depths of the four vertical cracks are (2.5, 5, 7.5 and 10 cm (1, 2, 3, and 4 in.), respectively. The deteriorated regions with reduced elastic modulus were prepared by inserting concrete blocks of a segregated or uniform size coarse aggregate. The magnitudes of the reduced modulus of the concrete blocks were estimated by measuring P-wave velocity through the concrete blocks and mass density of the block, resulting in about 60% of the solid concrete. Four cable conduit made of different materials (zinc, and platic), grouting conditions (fully-, and paritially-grouted), and steel strand in different conditions (with and without breakage) were inserted in the concrete. In addition, about 25% of the concrete deck was prepared for monitoring of chloride-induced deterioration through accelerated corrosion. Pockets of high chloride mix (15% of Cl$^-$ by weight) was placed on the five selected regions (CID 1 to 5) during casting. Consequently, 45 kg of natural sea salt was uniformly distributed over the regions and mixed during concrete pouring.

3.2 Acoustic scanning on the concrete bridge deck

The RABIT was programmed to automatically navigate and collect data on the concrete bridge deck (see Fig. 8). Two acoustic arrays inplemented in front of the the RABIT were used for acoustic scanning of the concrete speimen. The width of each acoustic array is 90 cm (3 ft), so it

covers a 180 cm (6 ft) wide strip of a bridge deck by unfolding two acoustic arrays on the deck surface. In this study only two scanning lines (see Fig. 8) were needed to cover the whole width of the concrete bridge deck. The RABIT automatically stopped every 30 cm (1ft) and performed IE and USW tests using the two acoustic arrays. At each test location, a single acoustic array took 16 time-records from 4 groups accelerometers (4 accelerometers in each group) and 4 impact sources. Consequently, a total of 1920 time signals (16x2x60) were taken and stored. To collect the data at a single tets point, which is composed of (i) stopping at the test point, (ii) data collection, and (iii) moving to the next point, took about 15 seconds. Therefore, the total time for scanning of the deck 3.6 by 9 m (12 by 30 ft) was about 20 minutes. This is a significantly reduced time, for a much larger volume of data, compared to conventional manual testing. Moreover, only two operators, one in the command van and the other on the concrete deck, were needed to conduct the data collection process.

3.3 IE and USW analyses

There are different ways of interpreting the severity of the delamination in a concrete deck with the IE method. One of the ways used in this study is shown in Fig. 8. The deck is described as solid or intact, if the dominant frequency corresponds to the thickness stretch modes (Lamb waves) family. In that case, the frequency of the fundamental thickness stretch mode (the zero-group-velocity frequency of the first symmetric (S_1) Lamb mode, or also called the IE frequency (f_{IE}). The frequency can be related to the thickness of a plate H for a known P-wave velocity C_p of concrete by

$$H = \beta_1 C_p / 2 f_{IE} \tag{1}$$
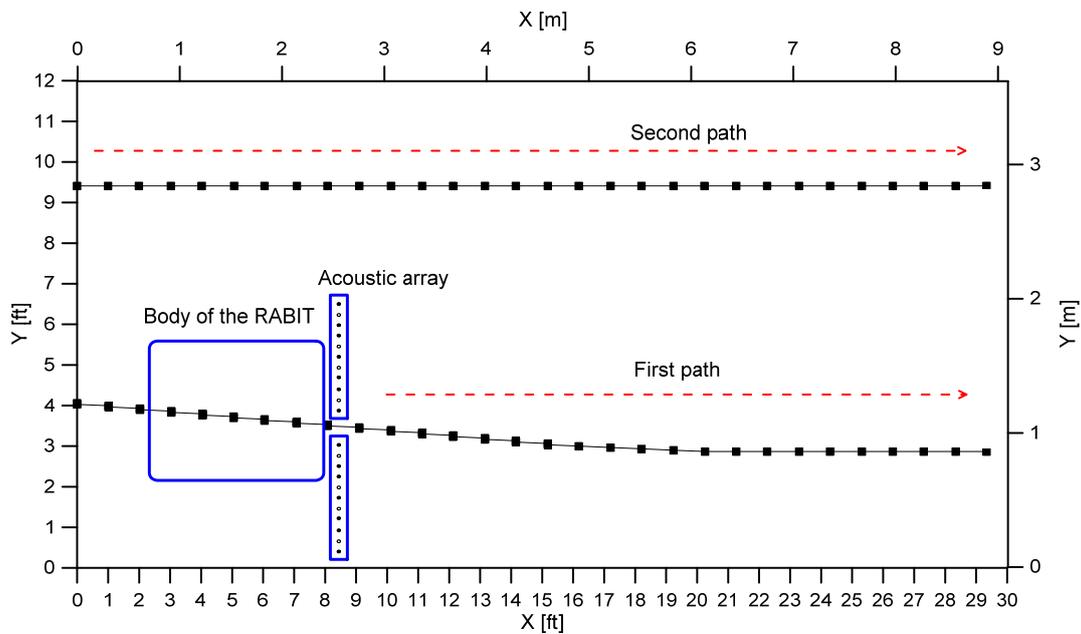
Fig. 8 Trajectory of the RABIT movement during the acoustic scanning

where β_1 is a correction factor that depends on Poisson's ratio of concrete, and is ranging from 0.945 to 0.957 for typical concrete. A delaminated point in the deck will theoretically demonstrate a shift in the thickness stretch mode toward higher values because the wave reflections occur at shallower depths. Depending on the extent and continuity of the delamination, the partitioning of the wave energy reflected from the bottom of the deck and the delamination may vary. The initial or incipient delamination, described as occasional separation within the depth of the slab, can be identified through the presence of dominant frequencies associated with the thickness stretch modes from both the bottom of the deck and the delamination. Progressed delamination is characterized by a single peak at a frequency corresponding to the depth of the delamination. Finally, in cases of wide or shallow delaminations, the dominant response of the deck to an impact is characterized by a low frequency response of flexural-mode oscillations of the upper delaminated portion of the deck. The four conditions are being assigned grades of sound, fair, poor and serious/severe, respectively.

The ultrasonic surface waves (USW) technique is an offshoot of the spectral analysis of surface waves (SASW) method used to evaluate material properties (elastic moduli) in the near-surface zone. The SASW uses the phenomenon of surface wave dispersion (i.e., velocity of propagation is a function of frequency or wave length) in layered systems to obtain the information about layer thickness and elastic moduli. The SASW test consists of recording the response of the deck (see Fig. 9), at two receiver locations, to an impact on the surface of the deck. The surface wave velocity as a function of frequency, termed the dispersion curve) is obtained by measuring the phase difference $\Delta\phi$ between the two sensors (sensor 1 and sensor 2) as follows
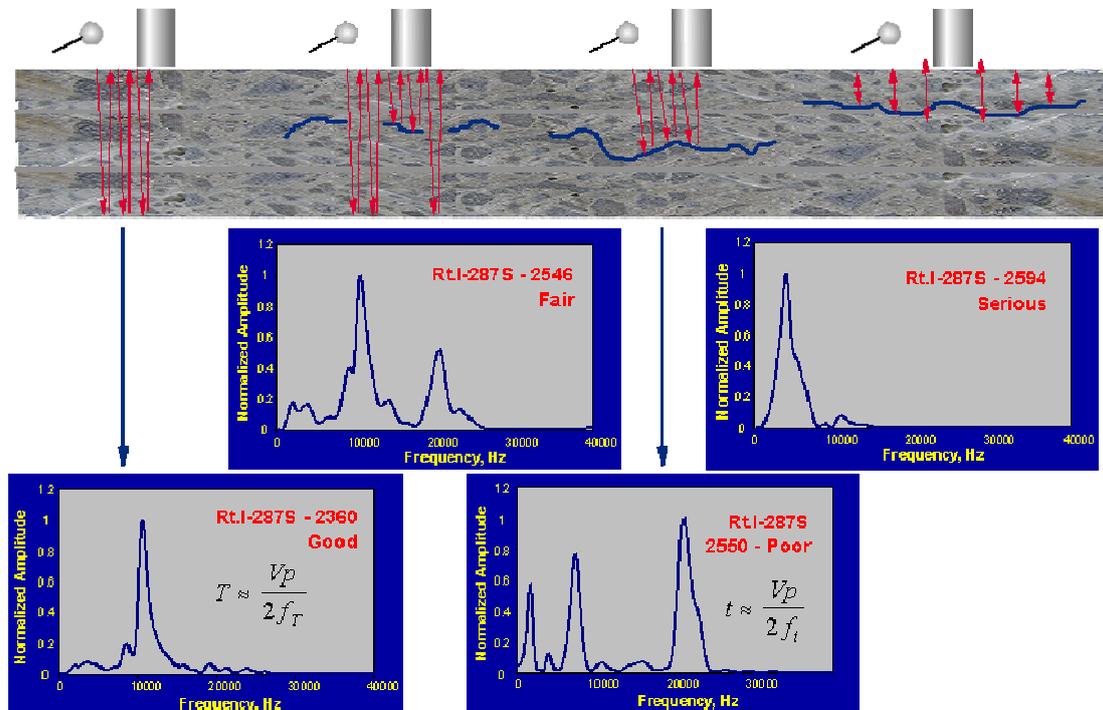
Fig. 8 Grades from IE testing for various degrees of deck delamination

$$\mathbf{C} = 2\pi f \frac{d}{\Delta\phi} \qquad (2)$$

where f is frequency and d is distance between two sensors. The USW test is identical to the SASW, except that the frequency range of interest is limited to a narrow high-frequency range in which the surface wave penetration depth does not exceed the thickness of the tested object. In cases of relatively homogeneous materials, the velocity of the surface waves does not vary significantly with frequency. The surface wave velocity can be precisely related to the material modulus, or concrete modulus in the case of bridge decks, using either the measured or assumed mass density, and Poisson's ratio of the material. In the case of a sound and homogenous deck, the velocity of the surface waves will show little variability. An average velocity is used to correlate it to the concrete modulus. A more rigorous way to obtain the modulus profile of the deck is by going through inversion or back calculation process (Ganji *et al*. 1998). Significant variations in the phase velocity (dispersion curve) are typically an indication of the presence of a delamination or other anomaly.

For the IE test, a single accelerometer was used to measure the dynamic response of the concrete deck. the following are the basic steps in the data analysis. The time domain signals are converted to the frequency domain using the fast Fourier trasform algorithm. A Hann window is applied to the raw time signals to eliminate contributions of the surface wave components, the very first high amplitude part of the signal. To increase the frequency resolution of the obatined spectra, a zero vector is added. In the anlaysis fo RABIT data a vector of 1024 zeros is added to provide a resolution of about 244 Hz. Typical signals from an IE test in the time and frequency domains are shown in Figs. 10 and 11. Time signals recorded over a solid or intact region (6G), over a deep delamination (11J), and a shallow delamination (9B) are shown in Fig. 10(a) through 10(c), respectively.
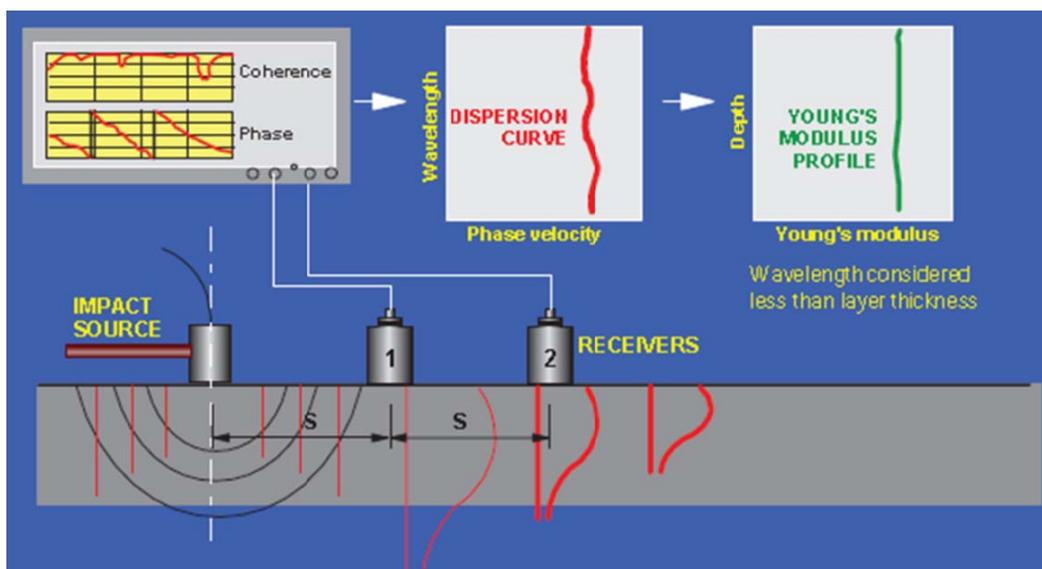
Fig. 9 Schematic of evaluation of concrete modulus by SASW (USW) method

The frequency spectra corresponding to the time signals shown in Fig. 10 are presented in Figs. 11(a)-11(c), respectively. The frequency response from the solid or intact regions shows a dominant peak frequency around 11 kHz, which matches well the full-thickness IE mode frequency calculated using Eq. (1). Shallow delaminations generate a low-frequency response, which in this case had a dominant frequency about 4.5 kHz as a result of flexural vibrations. Intermediate delaminations generate both flexural and thickness stretch modes, the second corresponding to the delamination depth. In contrast, deep delaminations at a 16 cm (6.5 in.) depth correspond to the thickness mode of about 13 kHz.

For the USW test, a pair of accelerometers (near and far receivers) was used to measure the surface wave velocity in the region between the two receivers. Typical time signals recorded by near and far receivers are shown in Fig. 12(a). A Hann window was applied to the raw time signals to extract the surface wave components, again the first high amplitude portions of the signal. Similarly to IE, a zero vector of a length of 1024 is added to increase the frequency resolution to about 244 Hz. The phase velocity of the surface waves were calculated using Eq. (2), and illustrated in Fig. 12(c). The phase difference (angle) shown in Fig. 12(b) is obtained from the phase of a cross-power spectrum of the two signals. More details on the calculation of the phase angle and development of the dispersion curve are provided in Nazarian *et al.* (1983). The elastic modulus based on the simplified procedure is shown in Fig. 12(d).
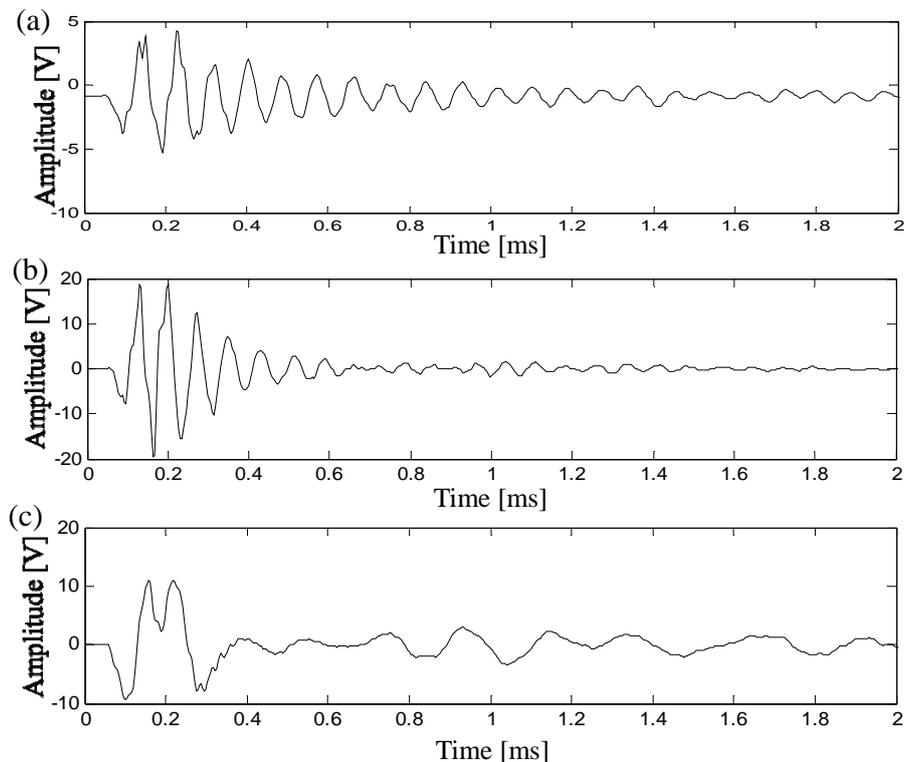
Fig. 10 Typical time records from the acoustic array for three deck locations: (a) (X,Y) = (6,G), (b) (11,J), and (c) (9,B)
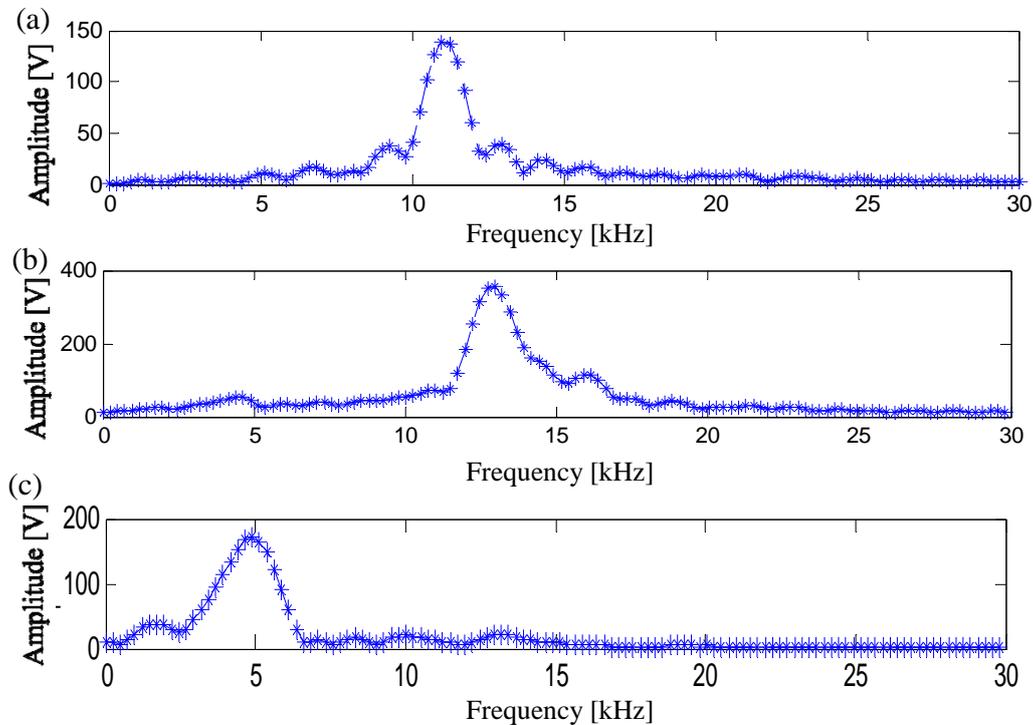
Fig. 11 Typical spectra obtained from the fast Fourier transform (amplitude) of the time signals shown in Fig. 10: (a) (X,Y) = (6,G), (b) (11,J), and (c) (9,B)

3.4 Condition maps

Fig. 13(a) is the delamination map based on the procedure illustrated in Fig. 8. The resulting condition map confirms that impact echo is effective in detecting and characterizing the most of the delaminations in the concrete deck. The locations of shallow delaminations (DL4, DL5, DL7 and DL11) shown as red spots or areas, indicating "serious condition" in the delamination map. Deep and intermediate delaminations are shown as green to yellow areas, indicating "fair to poor condition," respectively. However, the lower spatial resolution in the x direction hinders the ability to detect delaminations of short length in the x direction (e.g., DL10). In summary, the ability of the RABIT's IE array to detect and characterize delamination was demonstrated.

In addition, the locations of the areas with a reduced concrete modulus and with hollow or partially grouted ducts are also shown in the IE condition map. It can be seen that some of the artificial defects were missed in the condition map, primarily due to the lower spatial resolution. For the accelerated corrosion test region, the condition is marked as green to yellow, or "fair to poor" condition. The peak frequencies obtained in those regions are only slightly lower than IE frequency for the solid or intact regions. It can be physically interpreted that there is higher porosity and/or that micro cracks in concrete are developing due to corrosion activity in the salt contaminated test region, but have not caused delamination yet.
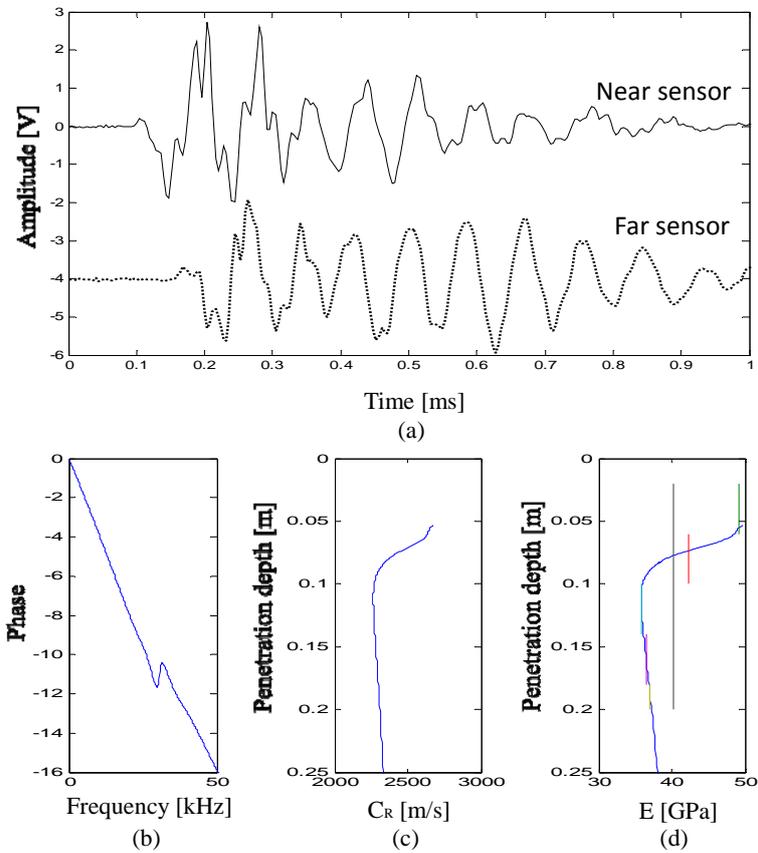
Fig. 12 USW procedure for calcualting elastic modulus of concrete: (a) typical time signals, (b) the phase angle versus frequency, (c) the dispersion curve (phase velocity versus wavelength), and (d) approximate elastic modulus of concrete versus depth

Fig. 13(b) is the concrete quality (modulus) map based on the USW method procedure illustrated in Fig. 9. The resulting modulus in the whole concrete deck ranges between 7.0 to 52.2 GPa with an average of 38.04 GPa and standard deviation of 8.46 GPa. Thus the coefficient of variation (COV) was about 22%. The COV of the USW on the validation slab appears to be little bit higher compared to the one by manual USW tests in the field, which is typically on the order of 10 to 20%. However, this variability more likely due to higher density of artificial defects in the validation slab than actual bridge decks.

The USW does not point to the locations of artificial defects for two reasons. The first reason is the physical principle of the USW measurement. The second reason is a lower spatial resolution of the USW test setup than of the IE test setup, as it was illustrated in Fig. 2. However, the USW condition map provides a reasonably good correlation to the IE condition map in the accelerated corrosion test region. As the corrosion activity has influenced the P-wave velocity and, thus, the dominant frequency response in the IE test, it has reduced the velocity of surface waves in the USW test. Therefore, the fusion of the IE and USW would result in more complete condition assessment of concrete under corrosion activity.
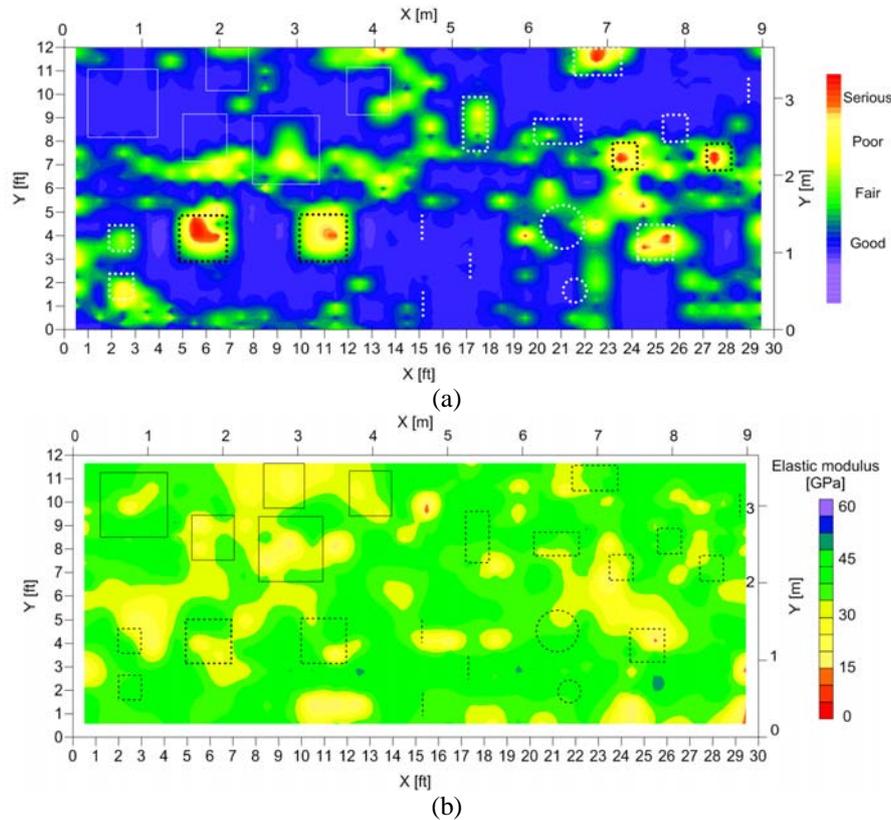
Fig. 13 Concrete condition maps from: (a) the IE and (b) USW tests using the RABIT's acoustic arrays

4. Conclusions

The RABIT system for data collection using multiple NDE technologies to characterize corrosion, delamination, and concrete degradation. The acoustic arrays play an especially important role, since they provide assessment with respect to delamination and concrete quality, or concrete degradation. The performance of two technologies used for that purpose: impact echo (IE) and ultrasonic surface waves (USW), was validated on a 9 m long and 3.6 m wide fabricated bridge structure with numerous artificial defects embedded in the deck. The resulting condition map confirms that impact echo is effective in detecting and characterizing the most of the delaminations in the fabricated concrete deck. Omission of two delaminations is attributed to the lower spatial resolution in the direction of the RABIT movement. The concrete modulus of the deck, as measured by the USW test, is in the expected range and the data dispersion corresponds to a typically observed modulus dispersion on actual bridges measured by manual NDE devices. The USW clearly identified a decrease in concrete modulus in the deck area undergoing accelerated corrosion. Since the decrease of wave velocities was observed in both the IE and USW tests, the fusion of the two would result in more reliable detection of concrete areas undergoing corrosion.

Even on this small bridge structure the high speed of RABIT's data collection was demonstrated. However, real benefits with respect to the speed of data collection are achieved on real bridges. From the RABIT deployment on a number of actual bridges, an average production rate with respect to data collection is estimated to be 350 m^2 of bridge deck area per hour. This speed of data collection opens opportunities for periodical data collection on a large number of bridges, or with multiple RABITs on a network level. Implementation of the RABIT within the LTBP Program will also enable comprehensive validation of the performance of embedded NDE technologies on actual bridges. This will be achieved through physical sampling, like coring and chloride concentration profiling, and comparisons with the results from a range of manual NDE technologies.

Acknowledgments

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