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Deterioration progression monitoring in concrete bridge decks using periodical NDE surveys

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ABSTRACT: Reinforced concrete decks are in most cases the fastest deteriorating component of a bridge due to a multitude of influencing factors. The study concentrates on the condition assessment of bridge decks using complementary nondestructive evaluation (NDE) techniques. The assessment consists of three main components: corrosive environment and corrosion processes, concrete degradation assessment, and assessment with respect to the deck delamination. Five NDE techniques: impact echo (IE), ground penetrating radar (GPR), half-cell potential (HCP), ultrasonic surface waves (USW) and electrical resistivity (ER), are utilized. A brief overview of the NDE techniques and their complementary use is illustrated by the results from bridge deck testing. Deterioration progression from periodical NDE surveys is illustrated by condition maps and condition ratings for the whole bridge deck and bridge deck segments. Different condition rating schemes, guided by different objectives of their usage, are presented. Those include: 1) condition rating comparisons of bridges on the network level for condition monitoring and rehabilitation, and 2) segmentation and rating on the project level to identify areas of the deck that should have higher priority in rehabilitation. In addition, samples of correlations between different NDE technology results are presented as one of the means to improve the confidence level of the condition assessment.

1 INTRODUCTION

American Society of Civil Engineers (ASCE) estimated that an annual investment of $17 billion is needed to improve the current bridge conditions (ASCE, 2009). The largest portion of this expenditure is allocated to bridge decks since they deteriorate faster than the other bridge components due to the traffic load and environmental effects (Gucunski et al., 2013). Nondestructive evaluation (NDE) technologies have excellent ability to objectively assess condition of reinforced concrete decks. They provide condition data with a high spatial resolution and can also objectively summarize the condition through condition rating indices. However, their implementation was mostly related, primarily due to the speed of NDE data collection and associated costs, to the assessment of decks for the purpose of near future rehabilitation. There is almost no NDE data for bridge decks describing deterioration progression, which could assist in development of more reliable deterioration, predictive and life cycle cost models.

Federal Highway Administration (FHWA) launched the Long Term Bridge Performance (LTBP) Program in 2008. As part of the LTBP Program, concrete decks of bridges throughout the United States will be periodically monitored using various NDE techniques. In the pilot phase of the LTBP Program, lasting three years, seven bridges representing the most common types of bridges nationwide were extensively investigated. Some of the bridges were re-evaluated after a period of two years. This provided an outstanding opportunity to demonstrate the ability of NDE technologies to detect and quantify deterioration progression in bridge decks.

The focus of the paper is characterization of progression of three major distresses: delamination, corrosion, and concrete degradation using five NDE techniques: ground penetrating radar (GPR), impact echo (IE), ultrasonic surface waves (USW), half-cell potential (HCP), and electrical resistivity (ER). A brief overview of the NDE techniques and their complementary use is illustrated by the results from bridge deck testing. Deterioration progression from periodical NDE surveys is illustrated by condition maps and condition ratings for the whole bridge deck and bridge deck segments. Different condition rating schemes, guided by different objectives of their usage, are presented. Those include: 1) condition rating comparisons of bridges on the network level for condition monitoring and rehabilitation, and 2) segmentation and rating on the project level to identify areas of the deck that should have higher priority in rehabilitation. Finally, some of the results of a correlation between different NDE technologies are presented, which can be used to increase the confidence level of detection.

2 NDE TECHNOLOGIES FOR BRIDGE DECKS

Bridge deck deterioration can be attributed to increased traffic volume, repeated traffic loading, exposure to deicing salt, environmental effects such as freeze-thaw cycles, etc. There are numerous deterioration phenomena observed in concrete bridge decks; delamination, corrosion, vertical cracking, carbonation, alkali-silica reaction, salt crystallization, creep, fatigue, etc. In particular, three types of deterioration are of the highest interest to bridge owners: delamination, rebar corrosion, and concrete degradation. The NDE technologies described below are utilized primarily for the detection and characterization of those three deterioration types.

The primary NDE technique used within the LTBP Program to detect and characterize the delaminated areas of the deck is impact echo (IE) (Sansalone, 1993). Impact echo method is an NDE technique based on stress wave propagation. The IE device used in the presented study is Stepper with three impact echo probes, as depicted in Figure 1. When the stress waves generated by an impact on the surface of a deck reach an interface with another material, a portion of the wave energy is reflected back to the surface, depending on the acoustic impedance contrast between the two media. When the reflectors are the bottom of the deck or a delamination (air), those will develop resonant modes, in which frequency can be measured and converted to the depth of the reflector. There is a special case of shallow or wide delamination, for which the response is dominated by low frequency flexural oscillations of the upper part of the deck. As illustrated in Figure 1, the IE data collection is conducted on a 0.6 by 0.6 m grid.

Corrosion is assessed within the LTBP Program through the measurement corrosive environment and corrosion activity. Electrical resistivity (ER) and half-cell potential (HCP) are used for that purpose, respectively. Electrical resistivity of concrete decreases as the moisture and chloride concentration increase (Whiting and Nagi, 2003). It has been observed that a resistivity of less than 5 kΩ.cm can support very rapid rebar corrosion (Brown, 1980). A four-point Wenner probe is used for resistivity measurements within the LTBP Program (Figure 1). Corrosion activity is, on the other hand, assessed using a rolling half-cell probe shown in the same figure. According to ASTM C876-09 “Standard Test Method for Half-Cell Potentials of

Uncoated Reinforcing Steel in Concrete", a measured potential more negative than -350 mV corresponds to a 90% probability of active corrosion. A measured potential less negative than -200 mV corresponds to a 90% probability of no active corrosion. Corrosion activity is uncertain if the potential is in the range of -350 mV to -200 mV. Similar to IE, HCP and ER measurements are conducted on a 0.6 by 0.6 m grid.

Figure 1. NDE technologies: Electrical resistivity measurement (top left) and probe (middle left), half-cell potential measurement (top right) and probe (middle right), GPR measurement (bottom left) and impact echo testing using Stepper (bottom right).

A quantitative assessment of concrete degradation is based on the ultrasonic surface wave (USW) measurement of the concrete modulus. Surface waves are stress waves traveling along the surface of the deck, with their body extending to the depth of, approximately, one wavelength. Therefore, as long as the USW testing is limited to the wavelengths within the order of the deck thickness, the surface wave velocity will be controlled by concrete properties. A qualitative assessment of the deck condition can be made using a GPR survey (Barnes and

Trottier, 2000). The presence of moisture, chloride ions, iron oxide, cracks, and air-filled delaminations increase the attenuation of electromagnetic waves. Thus, zones of highly attenuated signal in GPR attenuation maps indicate locations of likely concrete deterioration, delamination and/or corrosive environment. A GPR survey conducted using a 1.5 GHz ground-coupled antenna is shown in Figure 1.

3 RESULTS

3.1 Condition maps

Assessment of the deterioration progression is illustrated in Figures 2 and 3 by the condition maps obtained from ER and GPR surveys of a bridge in Virginia surveyed in 2009 and 2011. The ER map in Figure 2 describes concrete resistivity in kΩ.cm. The anticipated corrosive environment was defined based on correlations with other NDE methods. In this case, a threshold for corrosive environment was identified to be 40 kΩ.cm. The GPR attenuation map in dB, were threshold levels of deterioration were obtained from correlations with other NDE technologies. A condition of serious is described below -20 dB. The thresholds do not represent absolute attenuation levels, but are specific to the bridge conditions, equipment used, and the data analysis approach. The first main observation that can be made is that both technologies identify deterioration progression. In both cases expansion of deterioration and increase of severity of deterioration in 2011 occurs in the same areas identified as deteriorated in 2009. This fact increases confidence in the ability of NDE technologies to monitor deterioration progression through periodical measurements. Similar results, though not shown herein because of the space limitation, were obtained using the other NDE technologies, namely IE, HCP and USW. The second main observation is a high qualitative similarity between the ER and GPR condition maps. The similarity can be attributed to the fact that both measurements are primarily affected by the same elements affecting the electrical conductivity of concrete: moisture, chlorides, salts, etc. This correlation between ER and GPR is further discussed and illustrated in the following section.

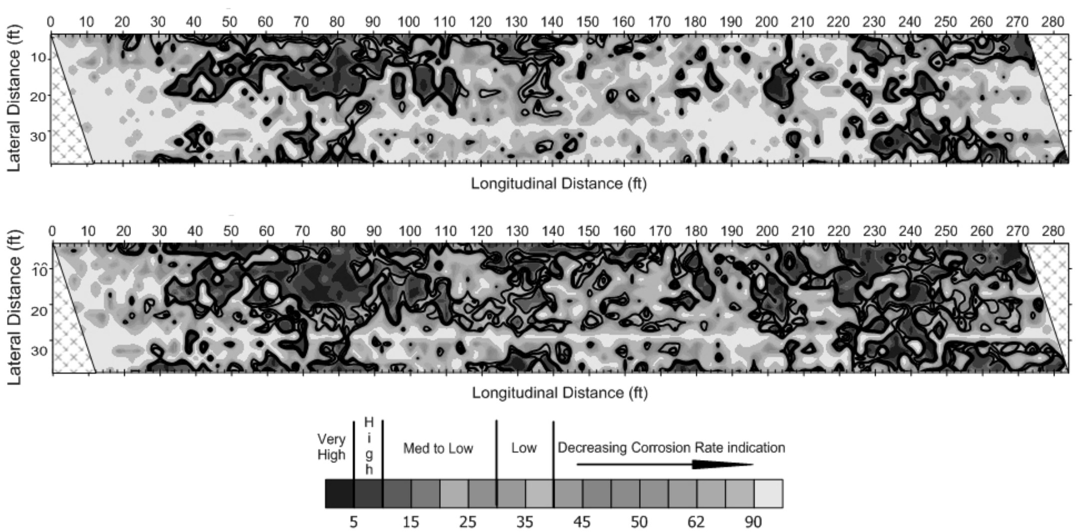

Figure 2. ER assessment of corrosive environment in 2009 (top) and 2011(bottom). The resistivity is described in kΩ.cm.

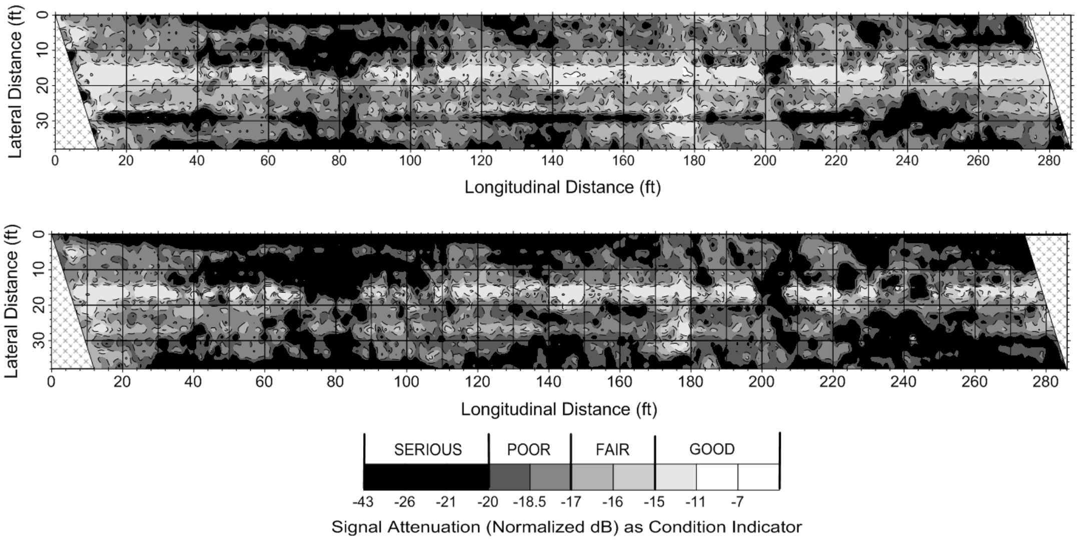

Figure 3. GPR condition assessment based on attenuation

3.2 Correlation between NDE technologies

The cumulative frequency distribution of the GPR amplitude for points that have a resistivity greater or less than 40 kΩ.cm is shown in Figure 4. When the resistivity is less than or equal to 40 kΩ.cm, 50% of the locations have a GPR amplitude less than -20 dB (GPR described limit for severe deterioration), and more than 95% of the locations have a GPR amplitude less than -15 dB (GPR described limit for unlikely deterioration). This is compared to only 10% (2009) and 23% (2011) of the locations with a resistivity greater than 40 kΩ.cm (low corrosive environment) have a GPR amplitude less than -20 dB (likely severe deterioration). These numbers illustrate strong agreement between resistivity and GPR signal attenuation, and to it anticipated deterioration.

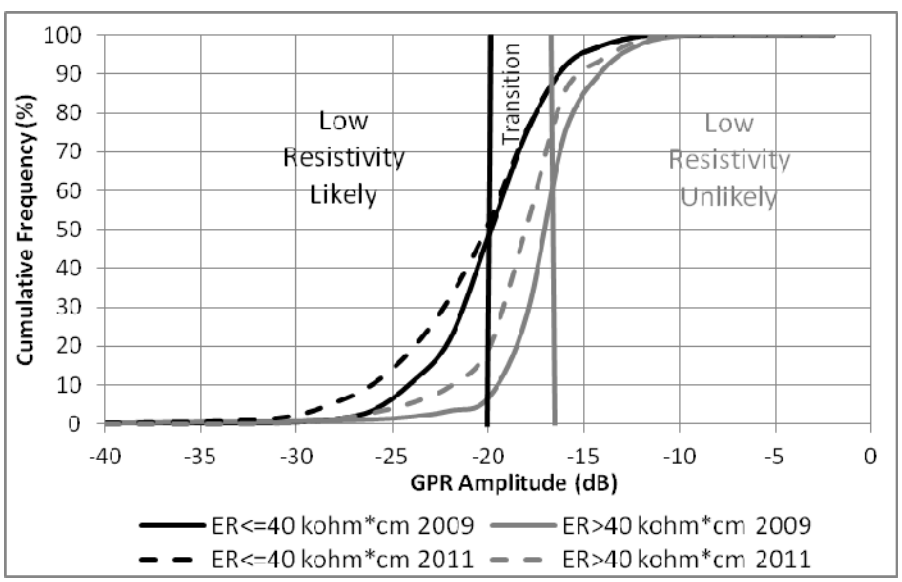

Figure 4. Cumulative frequency distribution of GPR amplitude for resistivity above or below 40 kΩ.cm.

The next illustration of NDE technology correlation is shown in Figure 5. It is a correlation between the HCP and ER results for the 2011 surveys. The areas below the thresholds for corrosion activity and corrosive environment are compared, i.e. areas below -350 mV for HCP and below 40 kΩ.cm for ER. As shown, there is an excellent correlation, with only smaller areas where only one technology, mostly ER, is below the threshold. Such a strong correlation between ER and HCP is expected, since a corrosive environment identified by ER is conducive to corrosion activity, identified by HCP. Since it is expected to observe corrosive environment before the development of corrosion activity, a larger area of ER measurements below the threshold is not surprising. Additional correlations were established regarding delamination detection between GPR and IE, and USW and IE, concrete degradation between USW and GPR, but are not presented herein for the space limitation. These correlations also point to corrosion as the primary cause of deterioration for this particular deck.

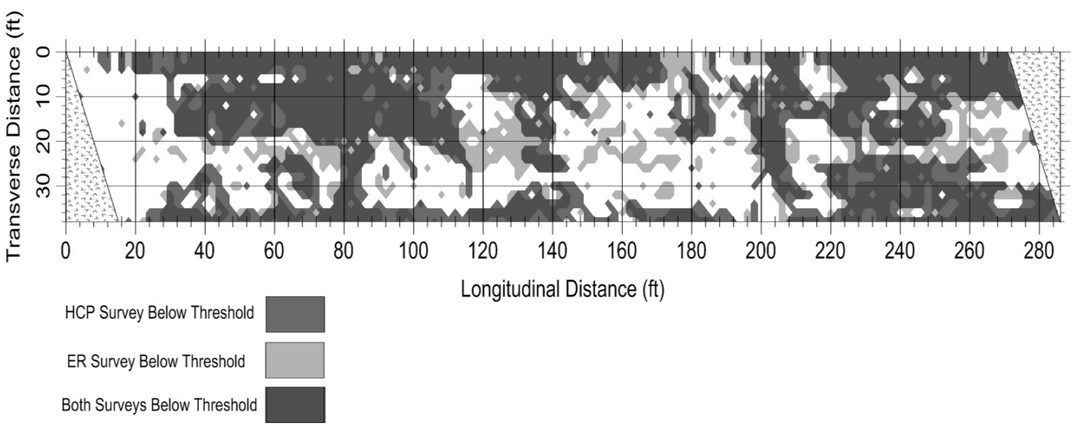

Figure 5. Correlation of ER and HCP below threshold areas.

3.3 Condition rating

The quantitative nature of NDE data can be exploited for a more objective condition rating of the deck and to more precisely quantify deterioration progression. It can be also used, in combination with bridge deck segmentation, to identify areas of the deck that should have priority in rehabilitation. This is illustrated in Figure 6 for the assessment of delamination in 2009 and 2011. The Virginia bridge deck in this case was divided into 18 segments and condition rating was calculated for each of them. Condition rating with respect to each of the deterioration or defect types is calculated using a weighted area approach. For example, the rating with respect to delamination, on a scale of 0 (worst) to 100 (best), is calculated from the weighted average of percentages of the areas falling into the three delamination conditions. The area described as sound (no delamination) is assigned a weight factor of 100. The area described in the state of initial delamination (fair to poor grade) is assigned a factor 50, and the area in the state of severe delamination a factor 0.

The same figure provides insight into progression of delamination in different segments of the deck. Clearly, all the segments incurred progression of delamination and, thus, a drop in the rating. The overall decrease in condition rating, shown in Figure 8, is well reflected in the increase of area of the deck in different stages of delamination. This is illustrated in Figure 7, where progression of delamination described by the increase of deck area in the severe condition, and in the initial or incipient state (fair and poor grades).

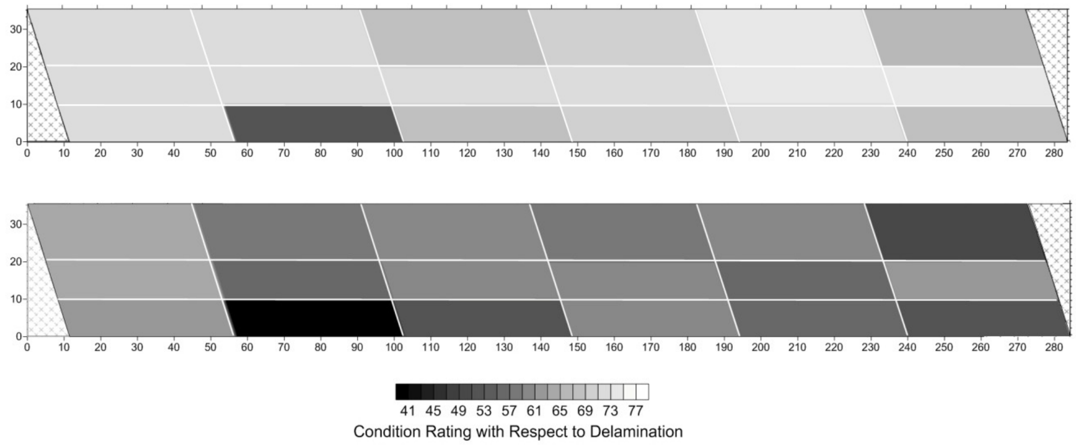

Figure 6. Condition rating of different segments of the Virginia bridge deck for 2009 and 2011.

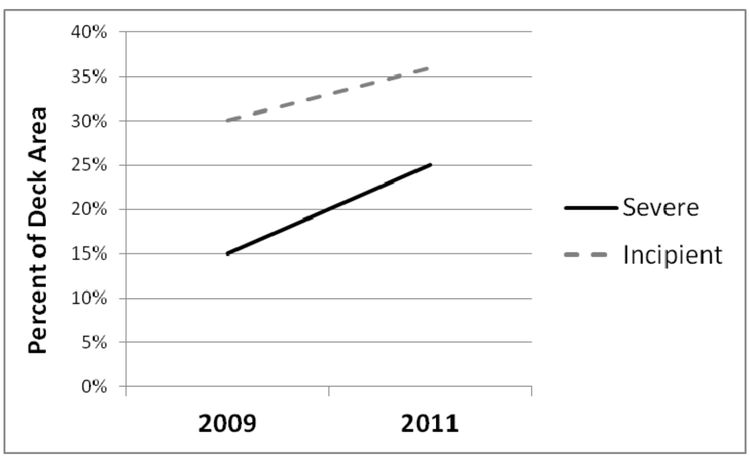

Figure 7. Change of percentage of deck area in different stages of delamination between 2009 and 2011.

The overall condition rating of a deck, and its change, can be defined from a weighted average of condition ratings obtained from different NDE surveys. This is illustrated in Figure 8, where the electrical resistivity results were used to calculate corrosion rating, impact echo results to calculate delamination rating, and GPR results to calculate concrete degradation rating. As illustrated, all three ratings dropped during the two year period at about the same rate. The overall rating was calculated as a simple average of the three. However, it is expected that bridge owners would assign different weights based on the importance of deterioration type.

4 CONCLUSIONS

Results of the surveys over a two year period have shown that NDE technologies have ability to objectively assess deterioration progression with time, whether it is described through increase of deteriorated areas or drop in condition rating. The complementary use of multiple NDE technologies enabled identification of corrosion as the primary cause of deterioration/damage. Finally, the bridge deck condition rating facilitates development of more objective and realistic deterioration and prediction models for concrete bridge decks.

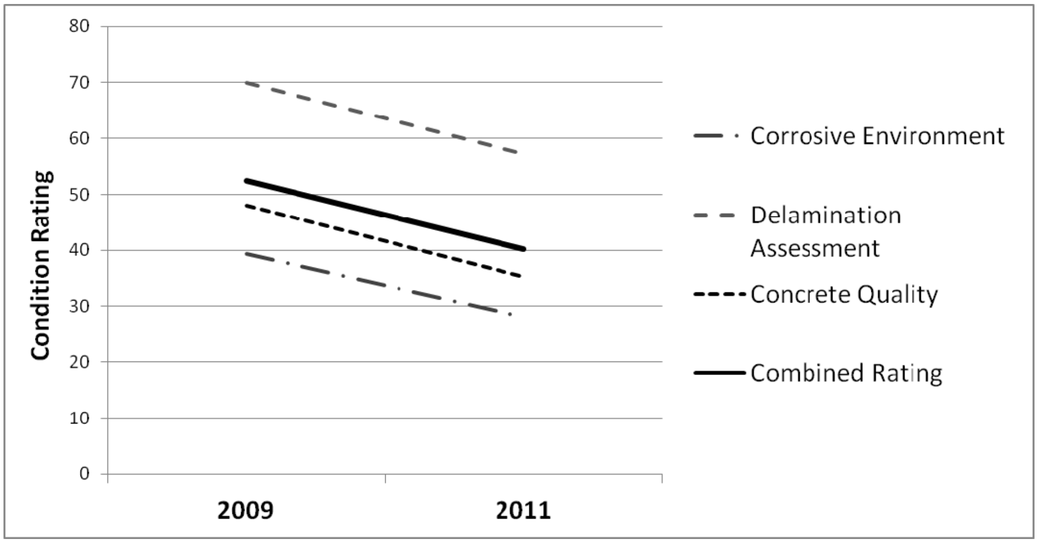

Figure 8. Change of condition rating with respect to corrosion, delamination and concrete degradation, and of the overall condition rating between 2009 and 2011.

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