Comprehensive Condition Assessment of Concrete Bridge Decks by Multiple NDE Technologies

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ABSTRACT: *From all bridge components, concrete bridge decks in most cases deteriorate the fastest. Therefore, the costs associated with their maintenance and rehabilitation represent the most significant part of the transportation agency budgets for bridges. The current practice of bridge deck inspection typically provides information when the deterioration is already in its latest stage. Main reductions in the expenditures can be achieved through their monitoring and assessment using nondestructive evaluation (NDE) technologies, and timely maintenance and repair. Since the currently used NDE technologies enable detection and characterization of only one deterioration type, the presented study concentrates on a complementary use of five NDE technologies: electrical resistivity (ER), half-cell potential (HCP), impact echo (IE), ground penetrating radar (GPR), and ultrasonic surface waves (USW) method. The technologies are used to assess condition of concrete decks with respect to rebar corrosion, delamination and concrete degradation. The results presented include maps describing the corrosive environment and corrosion activity, deck delamination, and quantitative and qualitative assessment of the concrete quality, and thus deterioration. Significant differences in the abilities of NDE technologies to characterize deterioration clearly points to the need for their complementary use to address the complex nature of deterioration in concrete bridge decks.*

1 INTRODUCTION

There are about 600,000 bridges in the United States of an average age of about 44 years. Because of the age, significant financial resources are devoted to their maintenance and rehabilitation. This is especially true for concrete decks, which deteriorate faster than other bridge components. Based on the interviews of the Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program research team with a number of state Departments of Transportation (DOTs), maintenance, rehabilitation and replacement of bridge decks constitutes between 50 to 80 percent of the overall expenditures for bridges. It is estimated that more than five billion dollars is spent annually in the U.S. on the maintenance, rehabilitation and replacement of bridge decks. Therefore, there is significant interest in developing means for their rapid and accurate condition assessment that would lead to significant savings through improved planning, better selection of intervention procedures, and reduced frequency and duration of traffic interruptions.

The high cost of bridge deck rehabilitation in the U.S. stems primarily from the lack of implementation of methods for early problem detection and rehabilitation. The dominant practice of state DOTs in evaluation of bridge decks is by visual inspection and the use of simple nondestructive methods like chain drag and hammer sounding (Figure 1). Such approaches, while having its own merits, in most cases provide information about the deck condition when deterioration has already progressed. On the other hand, NDE methods enable detection of deterioration processes at much earlier stages. Some state DOTs have been recently implementing use of single or possibly two NDE technologies in the assessment of bridge decks. The experience has been that, due to a composite nature of reinforced concrete and presence of multiple deterioration processes and defects, a diverse set of NDE technologies is needed for their comprehensive assessment.

Figure 1. Visual inspection (left), chain-drag (middle) and hammer sounding (right) of a bridge deck.

The paper has two main sections. In the first part of the paper, use of NDE in detection and characterization of three most common deterioration types: rebar corrosion, delamination and concrete degradation, are discussed. The NDE technologies discussed include: electrical resistivity (ER), half-cell corrosion potential (HCP), impact echo (IE), ground penetrating radar (GPR), and ultrasonic surface wave (USW) method. In the second part of the paper, results from actual bridge testing are presented and discussed with respect to the deterioration assessment and deck condition rating.

2 DETECTION OF DECK DETERIORATION BY NDE TECHNOLOGIES

There is a larger number of deterioration types of reinforced concrete, which can be of mechanical, chemical and even biological nature. The FHWA's LTBP Program assessment of bridge decks concentrates on rebar corrosion, delamination and concrete degradation. The five NDE technologies mentioned earlier are used for that purpose. The following sections discuss use of NDE in detection and characterization of each of the deterioration types.

2.1 Rebar Corrosion

Steel (rebar) corrosion is the most common cause of deterioration in concrete bridge decks is in the greatest part a result of (Figure 1). During the corrosion process, concrete allows electrolytic conduction and hence, the flow of ions from anodes to cathodes on rebars. Once the oxide film is destroyed, an electric cell is formed along the rebar or between rebars and the electrochemical process or corrosion begins. In addition, chloride ions typically penetrate from the surface into a bridge deck resulting in a higher salt concentration, more corrosive environment, and more negative electrical potential at the top reinforcing steel layer than at the bottom layer. The corrosive products on the rebars are of significantly larger volume than the original steel, leading to concrete cracking, delamination, and ultimately concrete spalling. The two elements, corrosive environment and corrosion activity, can be evaluated by ER and HCP methods, respectively.

Figure 1. Exposed corroded rebars (left) and a corroded rebar extracted with a core (right).

*The corrosion is initiated by the development of corrosive environment of concrete. Dry concrete will pose a high resistance to the passage of current, and thus will be unable to support ionic flow. On the other hand, presence of water and chlorides in concrete, and increased porosity due to damage and cracks, will increase ion flow, and thus reduce resistivity. This potential for corrosion of reinforcing steel can be well evaluated through measurement of electrical resistivity of concrete. The higher the electrical resistivity of the concrete, the lower will be potential for corrosion. Concrete that has electrical resistivity below approximately 40 kOhm*cm will promote corrosion. In contrast, dry concrete may have resistivity can exceed 100 kOhm*cm. Whiting and Nagi (2003) have related the electrical resistivity of concrete to the corrosion rates for reinforcing steel. ER measurement using the Wenner probe with four* *electrodes is shown in Figure 2. During the measurement the current is applied through two outer probes and the potential measured between the two inner probes. The electrical resistivity is calculated form the two.*

Half-cell potential (HCP) is used to measure corrosion activity. It involves the measurement of the electrical potential between the reinforcement and a reference electrode (usually copper electrode in a copper sulphate solution) coupled to the concrete surface. By moving the electrode from one point to another, or by using a wheel electrode (Figure 2), a potential map can be created. The ASTM C876 gives general guidelines for evaluating corrosion probability in concrete structures. According to the ASTM, points with potentials higher than -200mV have 90 percent probability of no active corrosion. On the other hand, points with potentials lower than -350mV have 90 percent probability of active corrosion. The measured potential values are influenced by both the corrosion activity and by the concrete cover and concrete resistance (Elsner, 2003).

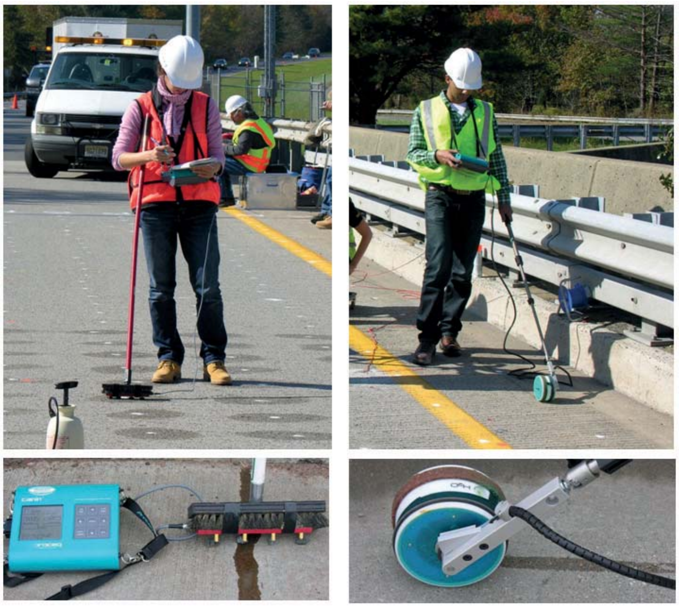

Figure 2. ER measurement using the Wenner probe (left) and HCP measurement using a wheel probe (right).

2.2 Concrete Delamination

Bridge decks are most commonly repaired because of delamination. Delamination can be described as a dominantly horizontal crack, most frequently on the top or bottom rebar levels. It is most often a result of rebar corrosion and, therefore, it often propagates from one to another rebar. However, delamination can be also a result of other types of concrete deterioration or repeated overloading, or a combination of those. Delamination was frequently detected in decks of bridges with flexible superstructure that highly deforms under passing heavy traffic. A couple of examples of progressed delamination detected in cores extracted from a bridge deck are shown in Figure 3. In one of theme, there was a previous attempt to repair it through epoxy injection.

Impact echo (IE) can both detect and characterize delamination in bridge decks with respect to the state of its progression (Sansalone, 1993 and 1997, Gucunski, 2000, Algernon and Wiggenhauser, 2006). The primary objective of IE testing is to determine dominant reflectors in the deck as a result of contrast in acoustic impedances of different materials. The highest contrast is at interfaces of concrete at air, which in most cases is the bottom of the deck or a delamination. The position of reflectors is obtained from resonant frequencies in the spectrum of the response of the deck due to a short duration impact. The response represents "standing waves" between the surface and the reflector. A typical frequency range of interest for IE assessment of concrete decks is between 1 and 25 kHz. Automated IE testing using

Stepper with three IE probes is shown in Figure 4. The impact ball and transducer are shown on the right side of the figure.

Figure 3. Cores extracted from delaminated bridge decks.

Various grades can be assigned in the condition assessment with respect to delamination. In the case of dominant resonances from the bottom of the deck, the deck is described as in a good condition. If a delamination is present, reflections occur at shallower depths, causing a shift in the dominant resonant peak towards higher frequencies. Depending on the extent and continuity of the delamination, the partitioning of energy of waves being reflected from the bottom of the deck and delamination may vary. Accordingly, various severity of delamination can be determined and graded. 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. This response is always in the audible frequency range and, thus, such delamination can be detected by chain drag or hammer sounding. This condition is described as serious or severe delamination.

2.3 Concrete Deterioration

Unlike delamination, concrete can deteriorate for a number of causes. Deterioration can be caused by repeated freeze and thaw, alkali-silica-reaction (ASR), mechanical stressing, overloading, etc. Other causes may include penetration of sulfates, which can attack concrete chemically, altering the microstructure of concrete and pore size distribution of the matrix. The by-products of these reactions are volumetrically larger than the original materials, thereby causing expansive stresses (cracks) within the concrete. In all the cases deterioration leads to either reduced mechanical properties or altered electrical/dielectric properties, or both. Ultrasonic surface waves (USW) method is effective in detecting and measuring changes in mechanical properties, elastic modulus in particular, while ground penetrating radar (GPR) will be effective in detecting changes in dielectric properties (dielectric constant and attenuation properties).

Figure 4. The Stepper (left) and impact echo probe (right).

The USW test utilizes the relationship between the velocity of surface waves in concrete and its modulus to assess its quality, or possible deterioration. In cases of mostly uniform materials, like concrete in bridge decks, the velocity is fairly constant for a limited range of wavelengths, less than the thickness of the deck (Nazarian et al., 1993). Variation in the phase velocity would be an indication of the variation of material properties with depth. In cases when the measurement is conducted at a point above a delamination, the measurement may show very low velocities and because of that a very low elastic modulus. Therefore, the USW can be used to some extent for delamination detection. One of the devices for USW testing, the portable seismic property analyzer (PSPA), is shown on the left side of Figure 5. It should be emphasized that lower modulus values do not necessarily mean deterioration. They can be also a result of material variation and placement procedures during construction. Therefore, a change in the concrete modulus from periodical measurements would be a more reliable way of detection of deterioration.

While the USW provide a quantitative, GPR provides a qualitative assessment of concrete deck deterioration through measurement of attenuation of electro-magnetic waves on the top rebar level. Concrete that is moist and high in free chloride ions, such as a deck that has undergone deterioration due to corrosion of the rebar, can significantly attenuate a GPR signal. These conditions, as discussed earlier, are defining the corrosive environment of the deck. Thus, similar to ER, results of GPR measurements are strongly influenced by the corrosive environment. A GPR survey of a bridge deck using a ground coupled antenna is shown on the right side of Figure 5. When the antenna is above or in proximity of a rebar, electro-magnetic waves are reflected from them. The amplitude of the reflection will be highest when the deck is in a good condition and weak when delamination and corrosion are present. Since the rebar depth can significantly influence signal attenuation, measured reflection amplitudes are corrected for variations due to the rebar depth. The deterioration threshold is established using ground truth, such as cores or other NDE results (Barnes and Trottier, 2000; Gucunski et al., 2005) to provide the results interpretation. Correlations with impact echo and chain drag/hammer sounding data have also shown that GPR has potential for delamination detection in areas of highly attenuated signal. Secondary results from the GPR surveys of bridge decks include the information about the deck thickness, concrete cover and rebar configuration (Romero et al., 2000; Barnes and Trottier, 2000).

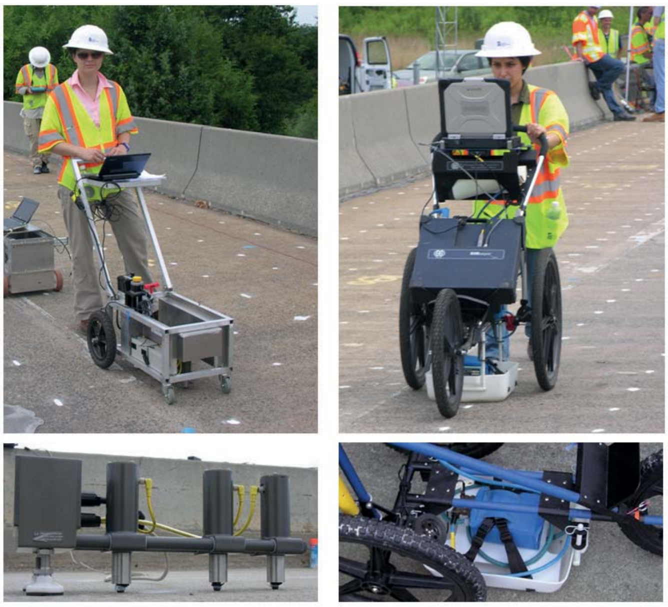

Figure 5 USW testing using PSPA (left) and GPR survey with a ground coupled antenna (right).

3 RESULTS OF MULTIPLE NDE TEHCNOLOGY EVALUATION

Condition assessment of bridge decks using such a multiple NDE technology approach is illustrated by the results of evaluation of two bridges in Iowa in Figures 6 and 7. The condition assessment from four technologies, namely HCP, ER, IE and GPR, is shown in Figures 6 and 7. For all NDE technology results, the hot colors (reds and yellows) represent high level of deterioration and the cool colors (blues and greens) low level of deterioration or a good condition. In the case of the bridge deck presented in Figure 6, all the technologies point to highest deterioration in the middle section, transversely, of the deck. Especially important, HCP and ER point to about the same areas as having active corrosion and corrosive environment, respectively. This points to a somewhat expected relationship between the corrosive environment and active corrosion. Similarly, there is a strong similarity between the ER and GPR condition maps, since the presence of corrosive environment affects both the electrical resistivity and GPR signal attenuation. Qualitative similarities between the three mentioned condition maps and the delamination map form the IE survey points to corrosion as the most likely primary cause of deterioration. Still, there are also differences in transition zones, where corrosion activity is not matched by presence of delamination, etc. For example, some IE identified delaminations are not identified by the GPR as zones of high attenuation. All of those are an illustration of how results from different NDE technologies complement each other in building a complete picture of bridge deck deterioration.

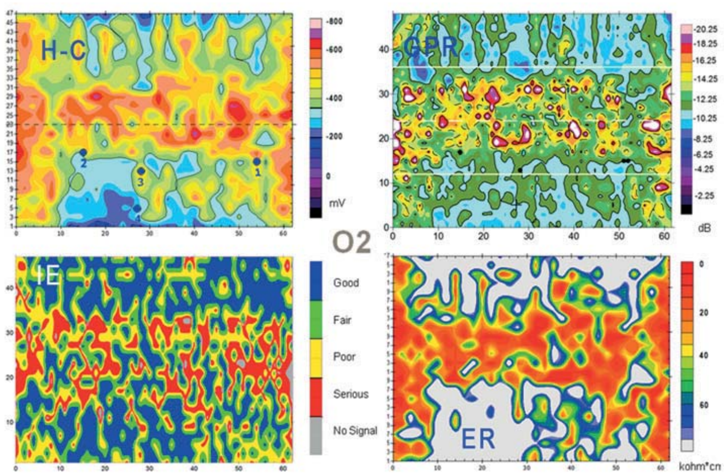

Figure 6. Condition assessment of the deck of a bridge in Iowa (O2) using HCP (upper left), GPR (upper right), IE (lower left) and ER (lower right).

On the other hand, there are significant differences in the results from different technologies for the bridge deck in Figure 7. The HCP results indicate little corrosion activity, while the IE map shows significant delamination. There are some similarities, but many more differences between the GPR and IE results. Therefore, in the case of this bridge deck, the primary cause of the deterioration is attributed to fatigue caused by repeated high deflection under heavy truck loads. This matches the observations made during the actual data collection.

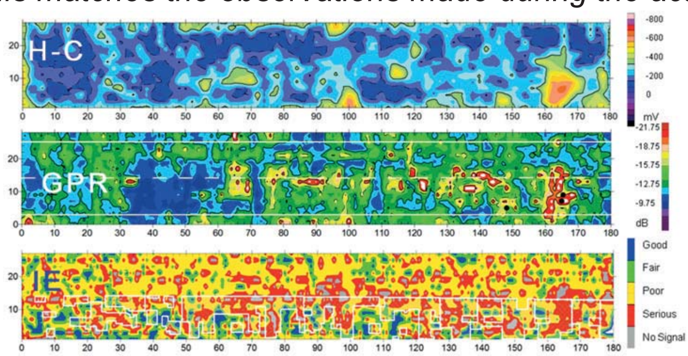

Figure 7. Condition assessment of the deck of a bridge in Iowa (O1) using HCP (top), GPR (middle), and IE (bottom).

4 CONCLUSIONS

Condition assessment of concrete bridge decks using multiple NDE technologies enables building of a more complete picture of deterioration. In addition, it can point to probable underlying causes of deterioration. The selection of the NDE technologies to be used in the deck survey should be guided by the anticipated causes of deterioration, and the deterioration of the highest interest.

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