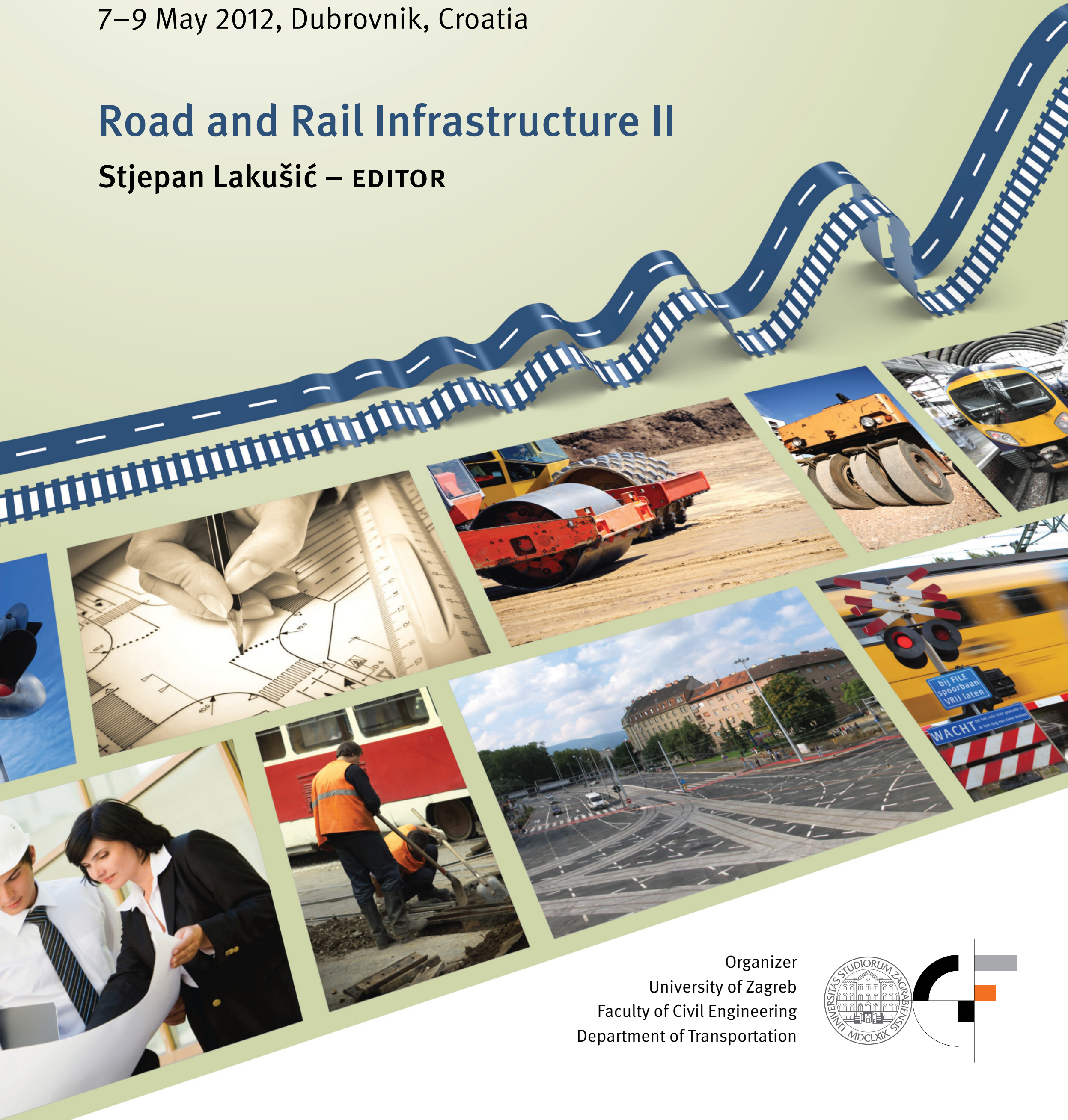
CETRA2012

2nd International Conference on Road and Rail Infrastructure

7–9 May 2012, Dubrovnik, Croatia

Road and Rail Infrastructure II

Stjepan Lakušić – EDITOR



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EXTENDING LIFE OF CONCRETE BRIDGE DECKS THROUGH EARLY DETERIORATION DETECTION BY NDE METHODS

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Abstract

Corrosion induced bridge deck delamination is a common problem in reinforced concrete decks. This is especially pronounced in the U.S.A. where far the highest percentage of concrete decks are bare decks. The prevailing inspection practice of bridge decks relies on visual inspection and the use of simple nondestructive evaluation (NDE) tools, like chain drag and hammer sounding. The presented study concentrates on a complementary use of five NDE techniques for the detection of three deterioration/defect types: corrosion, delamination and concrete degradataion. The NDE technologies used include: impact echo (IE), ground penetrating radar (GPR), half-cell potential (HCP), ultrasonic surface waves (USW) and electrical resistivity (ER). Each of the five techniques can contribute to a more comprehensive assessment of the condition of a deck. HCP provides information about the likelihood of active corrosion, while ER will assess the potential for corrosive environment. IE can accurately detect and characterize delaminations in the deck, while GPR can identify deteriorated bridge deck areas, in some cases matching the position of delaminations. Finally, the USW provides information about the material degradation through a measurement of concrete elastic modulus. One of the NDE features is that the results are quantitative. This allows objective assessment of the condition of a deck and, thus, objective comparison of bridges on the network level. In addition, NDE allows detection of problems at far earlier stages of deterioration than the traditional approaches. A brief overview of the techniques and their complementary use, illustrated by the results from deck testing on several bridges, is presented. Results include delamination maps from IE, attenuation maps from GPR, modulus distribution maps from USW, HCP potential maps, and resistivity maps from ER.

*Keywords: concrete decks, nondestructive evaluation, GPR, impact echo,
electrical resistivity, half-cell potential, surface wave testing*

1 Introduction

The dominant practice by state Departments of Transportation (DOTs) in the U.S.A. in evaluation of bridge decks is by visual inspection and the use of simple methods like chain drag and hammer sounding. Such an evaluation is somewhat subjective and can provide information about the deterioration when it is already in its fully developed stage. The presented study concentrates on a more objective condition assessment of bridge decks using a complementary use of nondestructive evaluation (NDE) techniques. The condition assessment has three main components: assessment of corrosive environment and corrosion processes, concrete degradation assessment, and assessment with respect to deck delamination. In all cases deterioration can be detected and quantified at all stages of progression, thus allowing more objective implementation of maintenance or rehabilitation strategies.

The following sections provide an overview of typical bridge deck deterioration and NDE methods used in their detection. The NDE of bridge decks and condition rating is illustrated by the examples from bridge deck evaluation within the Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program. The NDE technologies used in the assessment include: half-cell potential (HCP), electrical resistivity (ER), ultrasonic surface waves (USW) ground penetrating radar (GPR), and impact echo (IE) method. In addition, because the the data obtained from NDE surveys are quantitative, a more objective condition rating of bridge decks can be made. The rating can serve multiple purposes: it allows accurate monitoring of deterioration progression with time, and thus its better prediction, it allows more objective comparison of bridges on the netwrok level, and it allows better identification of more deteriorated sections of a bridge through segmentation. Different condition rating schemes, guided by different objectives of their usage are illustrated.

2 Concrete deck deterioration and its detection

2.1 Concrete deck deterioration

There are many causes of concrete deck deterioration that can be of chemical (e.g. alkali-silica reaction, carbonation), physical (creep, fatigue, overloading, shrinkage, etc.) and even biological nature. However, the prevailing cause of deterioration in concrete bridge decks is a result of rebar corrosion. The rebar corrosion will cause concrete cracking and ultimately lead to bridge deck delamination and spalling. This is illustrated in Figure 1.

Figure 1 Rebar corrosion, delamination and concrete degradation.

Understanding the causes of deterioration, and anticipated defects as a result of deterioration, is essential in identifying the best techniques for their detection and characterization.

2.2 NDE methods for concrete deck deterioration detection

The following sections describe technologies used in assessment of corrosion, concrete quality and deterioration, and delamination. There are a number of ways corrosion in concrete decks is assessed. These include evaluation of corrosion activity, measurement of corrosion rate, description of concrete as a corrosive environment, etc. Half-cell potential and electrical resistivity are two most commonly used NDE methods in corrosion assessment of a reinforced concrete elements. The HCP measurement is a simple way to assess the probability of steel corrosion, while ER measurement of concrete describes the corrosive environment and thus potential for corrosion of reinforcing steel. HCP involves the measurement of the electrical potential between the reinforcement and a reference electrode (usually copper electrode in a copper sulfate solution) coupled to the concrete surface (Figure 1 left). A more negative potential indicates a higher probability of corrosion. The measured potential is somewhat influenced by the concrete cover and the concrete resistance, which varies with moisture content, temperature and ion concentrations [1].

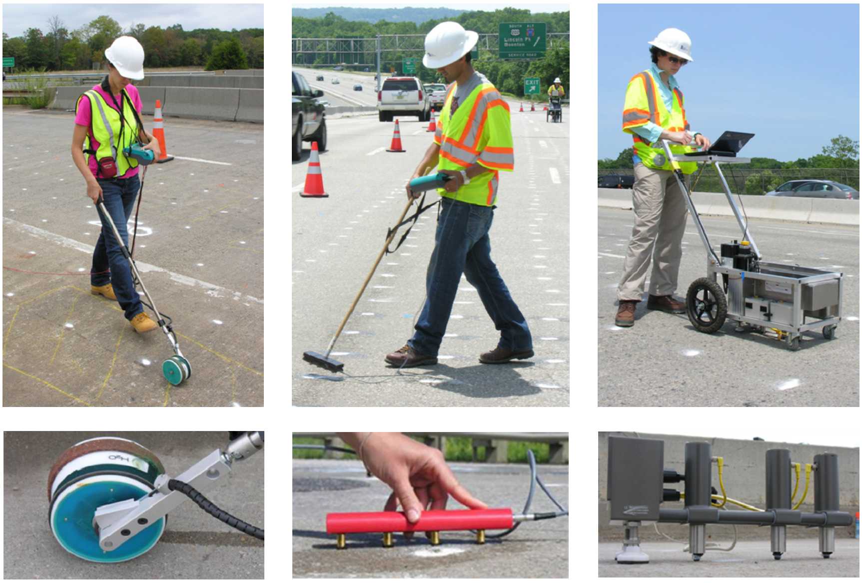

Figure 2 HCP testing and reference electrode (left), ER measurement and Wenner probe (middle), and USW measurement and PSPA (right).

The electrical resistivity of concrete is highly influenced by presence of mositure and chlorides. The lower the resistivity the higher the corrosion current passing between the anodic and cathodic areas of the reinforcing steel will be. It has been observed that a resistivity of less than 5 kohm*cm will support very rapid rebar corrosion, while a resistivity higher than 30 kohm*cm will not promote corrosion. In many cases the electrical resistivity can be related to the rebar corrosion rate [2].The most commonly used probe for resistivity measurement is the Wenner probe (Figure 2 middle). It uses four equally spaced probes (electrodes). A current is applied between the outer electrodes and the potential measured across the two inner ones to obtain concrete resistivity.

Ultrasonic surface wave (USW) method enables quantitative assessment of concrete through the measurement of concrete elastic modulus. The modulus is obtained from the measured surface wave velocity for wavelengths shorter than the deck thickness, and assumed or measured concrete density and Poisson's ratio. In concrete decks, the velocity is fairly constant for that range of wavelengths [3]. Variation in the phase velocity is an indication of the variation of concrete modulus with depth, or delamination when there is a significant drop in the measured modulus. One of the devices that can be used for USW testing is portable seismic property analyzer (PSPA) (Figure 2 right).

Figure 3 Delamination detection using IE (left) and GPR survey (right).

Ground penetrating radar (GPR) provides a qualitative assessment based on the measurement of signal attenuation on the top rebar level. Electrical conductivity and dielectric properties play the primary role in how a GPR signal travels, disperses or reflects within construction materials. Both are significantly influenced by the presence of moisture, chlorides, salts, etc., especially if concrete is cracked and delaminated. The amplitude of the reflection will be highest when the deck is in a good condition and weak when corrosion and cracking are present. Amplitudes for all points are normalized with respect to the best possible condition and corrected for variations due to the rebar depth to obtain the attenuation plot. A unique deterioration threshold for each deck is established using ground truth, such as cores or other NDE methods [4]. In many cases good correlations were observed between the delaminations detected by impact echo, and the zones of high attenuation in the GPR maps. Bridge decks have been evaluated using a variety of GPR systems [5]. However, ground coupled antennas provide more detailed imaging and analysis of the deck condition (Figure 3 right).

3 NDE survey results

NDE surveys on bridge decks within the LTBP Program are done on a 60 by 60 cm grid, as shown in Figure 4. The results are typically presented in terms of condition maps and calculated condition rating for a particular deterioration type and the overall bridge deck condition. The following sections provide illustrations of the condition mapping and rating, and their application in condition monitoring.

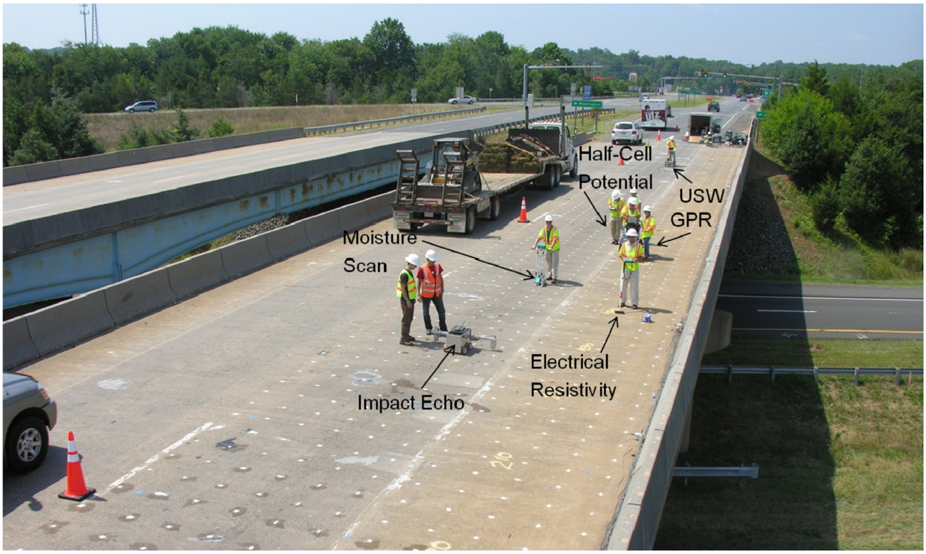

Figure 4 NDE survey of a bridge in Virginia.

3.1 NDE condition maps

Condition assessment maps of a California bridge evaluated as a part of the LTBP Program are shown in Figure 5. The maps were obtained (top to bottom) from the five described technologies: HCP, ER, USW, IE and GPR. In general, warm colors (yellow and red) indicate deterioration or defect, while cold colors (green and blue) indicate fair or good condition. It can be oberved that HCP and ER point to low to no corrosion activity and weak corrosive environment, respectively. The two maps confirm the expected relationship between the two: a corrosive environment is the primary requirement for active corrosion. This result was somewhat expected because of very dry climatic conditions in the bridge area. However, some deterioration still can be observed in IE and GPR maps. The deterioration was likely a result of other causes, like fatique or overloading.

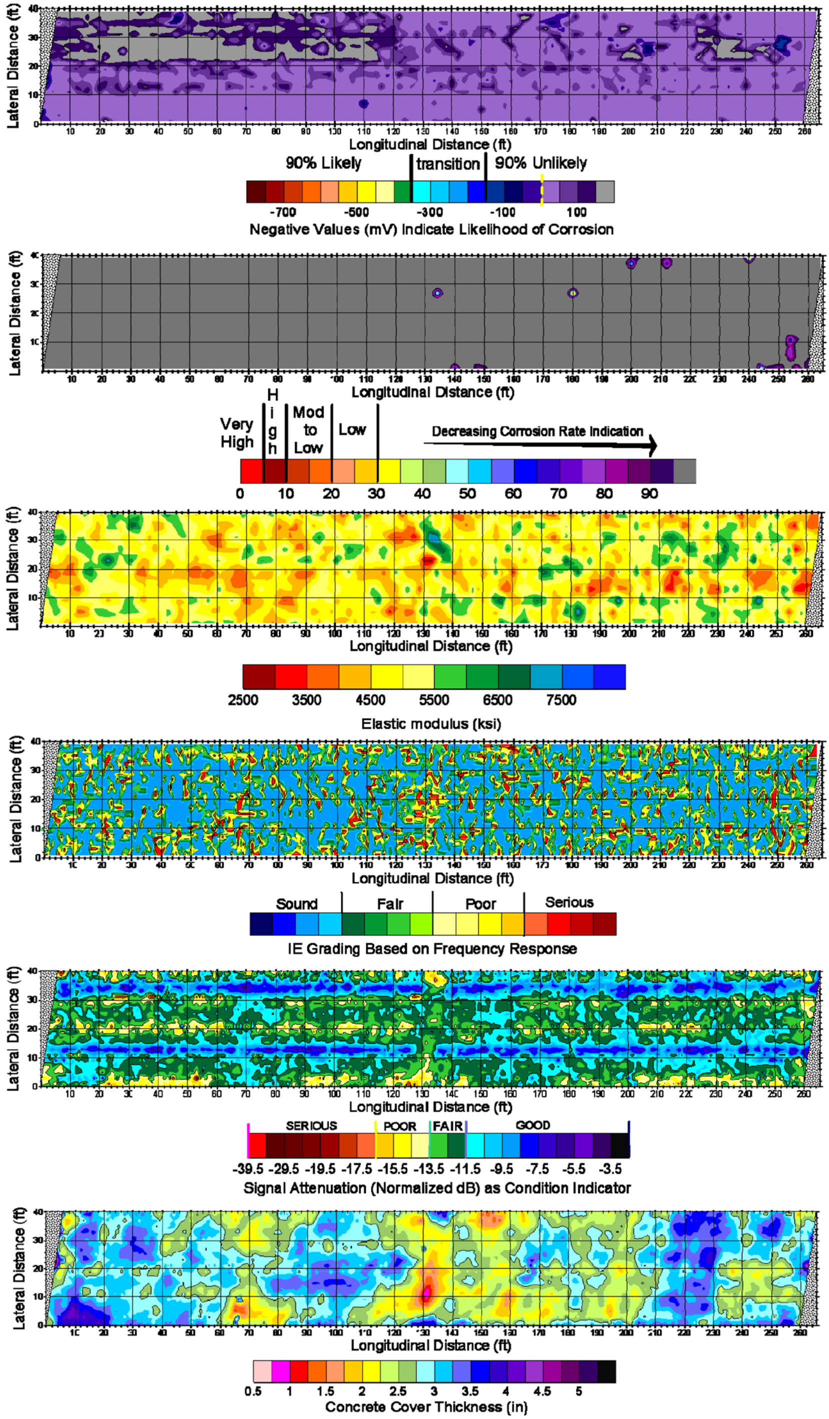

Figure 5 Condition maps from NDE surveys: HCP, ER, USW IE, GPR attenuation map and concrete cover (top to bottom).

Areas of very low concrete modulus obtained from the USW testing are, in general, at locations of delamination identified by impact echo. Finally, the secondary product of GPR testing, the concrete cover map is shown at the bottom of Figure 5. In many cases the detected corrosion induced deterioration can be attributed to low concrete cover.

3.2 Deterioration progression monitoring and condition rating

The condition maps from ER survey in 2009 and 2011 for the Virginia bridge shown in Figure 4 are shown in Figure 9. Quiet clearly, a progression of deterioration can be observed during the two year period. Similar results were obtained, but not shown herein, for the other technologies.

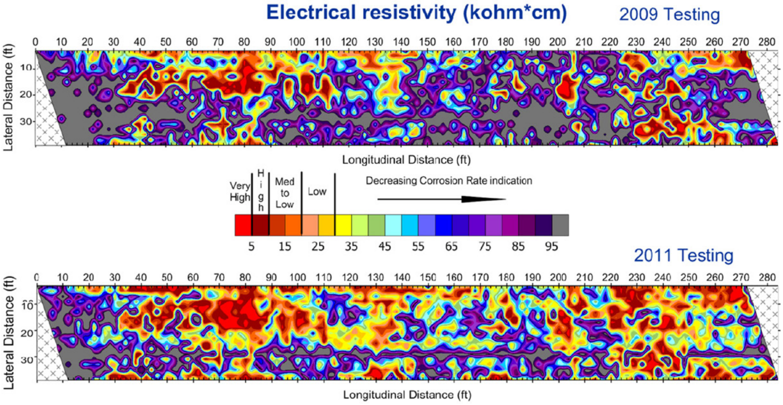

Figure 6 Electrical resistivity maps from 2009 and 2011 for the Virginia bridge.

Because of the quantitative nature of NDE results, a more objective assessment of bridge decks can be made by determining a bridge deck condition rating. The condition rating with respect to each deterioration or defect type is calculated using a weighted area approach. For example, the overall rating on a scale 0 to 100 (best), with respect to delamination is calculated from the percentages of areas falling into three states. The area described as sound is assigned a weight factor 100, the area in the state of progressed delamination (serious condition) a factor 0, and the area of the incipient delamination (fair to poor grade) is assigned a weight factor 50. Different weight factors could be applied to better reflect the experience and judgment of a bridge owner. The overall condition rating of a deck can be defined from a weighted average of condition ratings obtained from different NDE surveys and visual inspection. This is illustrated in Table 1 for the same Virginia bridge using the HCP results for corrosion activity rating, IE results for delamination rating, and GPR results for concrete degradation rating. The overall rating was calculated as a simple average of the three. The table also summarizes the changes in rating that occurred during a two-year period for different sections of the bridge deck.

Table 1 Deck condition rating for Virginia bridge for 2009 and 2011.

	2009	2011
Active Corrosion	39.4	28.1
Delamination Assessment	70.0	57.2
Concrete Degradation	48.1	35.3
Combined Rating	52.5	40.2

4 Conclusions

NDE technologies enable detection and characterization of deterioration processes at all stages of development. Complementary use of NDE technologies leads to a more comprehensive condition assessment and in many cases may assist in identification of underlying causes of deterioration. Because of the quantitative nature of the NDE results, more objective assessment of the deck condition can be obtained by determining the condition rating. The rating based approach enables more objective rehabilitation prioritization on the network level.

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