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Condition monitoring of concrete bridge decks through periodical NDE using multiple technologies

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ABSTRACT: Maintenance and rehabilitation of reinforced concrete decks damaged by various deterioration processes represent significant cost to transportation agencies. Main reduction in the expenditures can be achieved through their monitoring and assessment using NDE technologies, and timely maintenance and repair. While condition assessment can be done using a number of traditional and NDE methods, the presented study concentrates on a complementary use of five NDE techniques: impact echo (IE), ground penetrating radar (GPR), half-cell potential (HCP), ultrasonic surface waves (USW) and electrical resistivity (ER). Results presented include: a delamination map from IE, a condition assessment map based on electromagnetic wave attenuation from GPR, a map of probable active corrosion from HCP, and a concrete resistivity map from ER. Some of the results were validated through a series of "ground truth" measurements, like inspection of cores taken from the decks. The presented results point clearly to the need for complementary NDE using multiple technologies to address the complex nature of deterioration in concrete bridge decks. The quantitative nature of NDE results enables rating of the deck and its segments with respect to evaluated deterioration type, which might assist on prioritization on both network and project levels.

1 INTRODUCTION

Maintenance and rehabilitation of concrete decks represents the highest expenditure in the state DOT budgets for bridges. Based on the interviews of the Long Term Bridge Performance (LTBP) Program research team with a number of state DOTs, maintenance, rehabilitation and replacement of bridge decks constitutes between 50 to 80 percent of the overall expenditures for bridges. As such, having means for rapid and accurate condition assessment of bridge decks could lead to significant financial benefits through: better planning, better selection of intervention procedures, and reduced frequency and duration of traffic interruptions.

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. Such approaches, while having its own merits, in most cases provide information about the deck condition when deterioration has already progressed. Nondestructive evaluation (NDE) methods, on the other hand, enable detection of deterioration processes at their early stages. Some state DOTs have implemented NDE technologies. However, very often those would rely on the application a single or maybe a couple of NDE technologies. Due to the composite material nature of concrete and presence of a whole suite of deterioration processes and defects, a diverse set of NDE technologies is required for their assessment.

The paper describes application of five NDE technologies in bridge deck evaluation. The technologies implemented during the surveys include half-cell corrosion potential (HCP), electrical resistivity (ER), impact echo (IE), ground penetrating radar (GPR), and ultrasonic surface wave (USW) testing. The firts part of the paper discusses detection and characterization of three most common deterioration types: rebar corrosion, delamination and concrete degradation. IN the second part, results from a bridge testing in Virginia are presented and include: a delamination map from IE, a condition assessment map from GPR, a map of probable active corrosion from HCP, and a concrete resistivity map from ER.

2 DECK DETERIORATION AND CORRESPONDING NDE TECHNOLOGIES

2.1 Rebar Corrosion

Deterioration in concrete bridge decks is in the greatest part a result of steel (rebar) corrosion (Figure 1). During the 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 two elements, corrosion activity and corrosive environment, can be evaluated by HCP and ER methods. Rebar corrosion leads to concrete deterioration, delamination, contamination and loss of rebar section. If the corrosion involves large areas, it will cause large cracking and delaminations, and ultimately spalling of concrete.

Figure 1. Rebar corrosion.

Half-cell potential (HCP) and electrical resistivity (ER) are the most commonly used NDE methods to define the corrosive environment of concrete decks. HCP 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 measured potential values are influenced by both the corrosion activity and by the concrete cover and concrete resistance (Elsner, 2003). In general, regions with a more negative potential indicate a higher probability of corrosion. The ASTM C876 gives general guidelines for evaluating corrosion probability in concrete structures. HCP measurements cannot give quantitative information about the actual corrosion rate of the reinforcement.

The corrosive environment of concrete and thus 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 the corrosion current passing between the anodic and cathodic areas of rebars. 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 resitivity. It has been observed that a resistivity less than 5 kohm*cm can support very rapid corrosion of steel (Brown, 1980). 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. Measurement of electrical resitivity using the Wenner probe is shown in Figure 2.

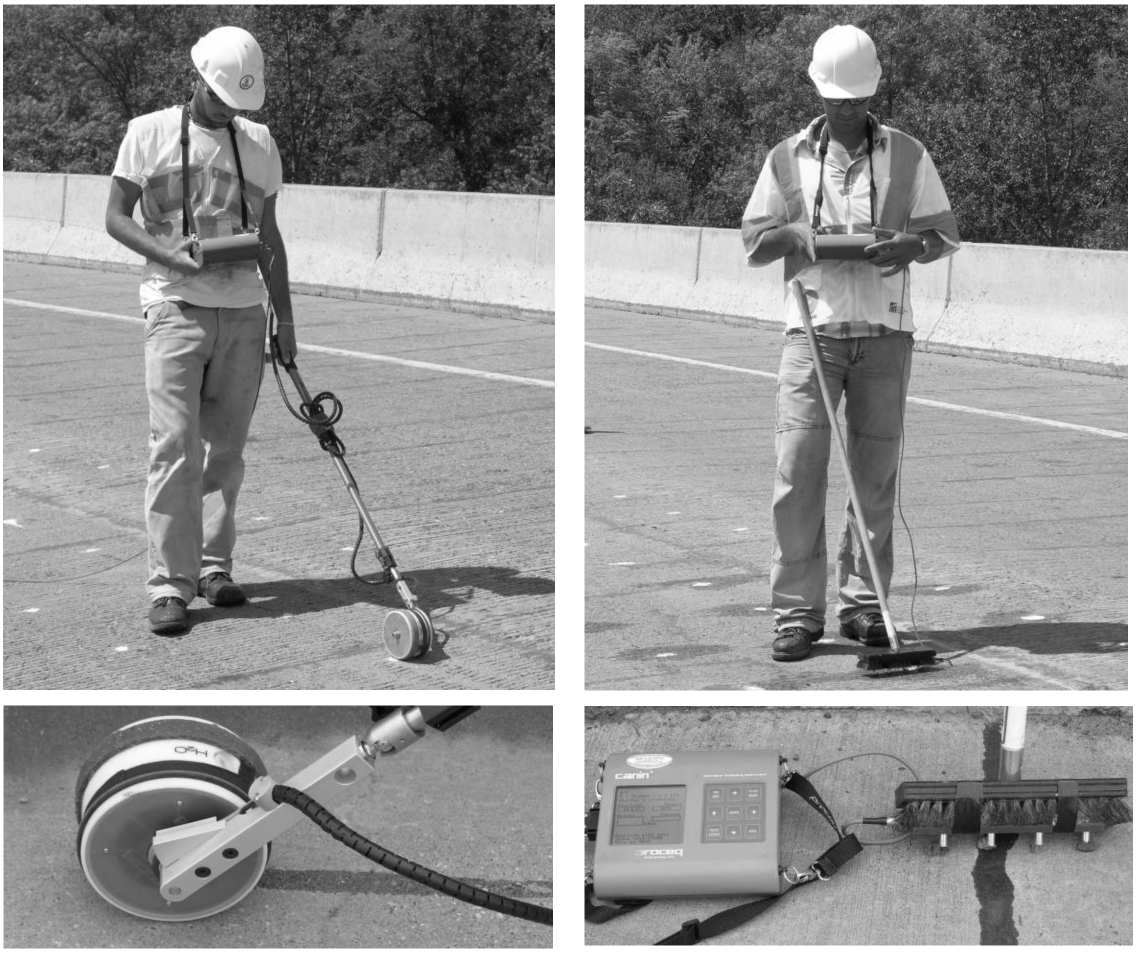

Figure 2. HCP measurement using a wheel probe (left) and ER measurement using the Wenner probe (right).

2.2 Concrete Delamination

Concrete delamination is most often a result of rebar corrosion. During the corrosion, the buildup of corrosive products on a rebar causes a significant increase in the rebar volume over the original one. The pressure of the increased volume induces cracking and further delamination of concrete. However, delamination can be also a result of other types of concrete deterioration or repeated overloading, or a combination of those. An example of what can be described as initial delamination, a thin crack propagating from one to another rebar, is shown on the left side of Figure 3. A progressed delamination is shown on the right side of the same.

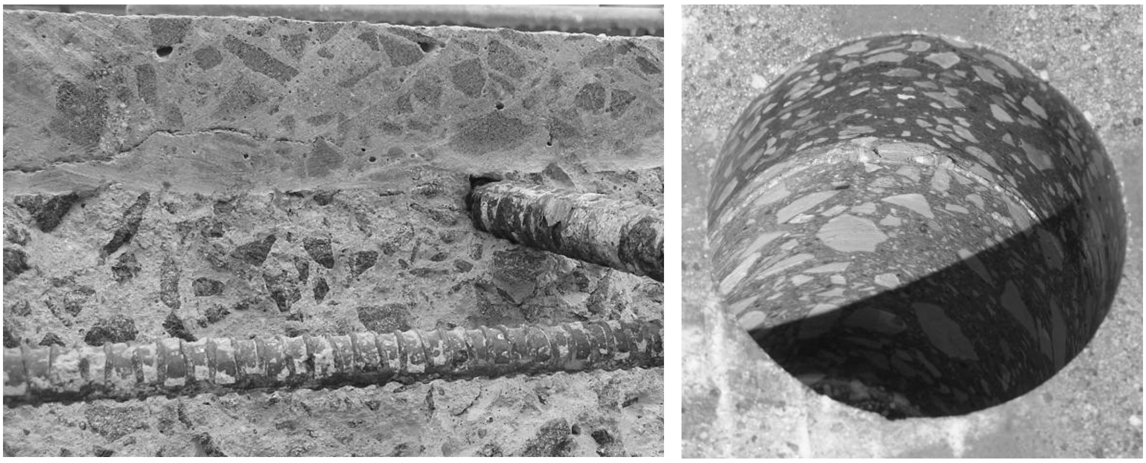

Figure 3. Initial (left) and progressed delamination (right).

Impact echo (IE) has been successfully implemented in detection and characterization of delamination in bridge decks (Sansalone, 1993 and 1997, Gucunski, 2000 and 2008, Algernon and Wiggenhauser, 2006). The primary objective of IE testing is to determine dominant reflectors in the deck, which are in most cases the bottom of the deck or a delamination. IE is a frequency response method. Thus, the position of reflectors is obtained from resonant frequencies of „standing waves“ between the surface and the reflector. IE testing using Stepper, developed at BAM (German Federal Institute for Material Research and Testing), is shown in Figure 4. The impact ball and transducer are shown on the right side of the figure. The Stepper allows automated data collection at a prescribed spacing between data points.

Four grades are typically assigned in the condition assessment with respect to delamination. In the case of strong reflections from the bottom of the deck, the deck is described as good. In the case of a delaminated deck, reflections of the compression wave occur at shallower depths, causing a shift in the response spectrum 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. Initial delamination (fair condition) is described as occasional separations between the two deck zones. Thus it will have two distinct peaks corresponding to reflections from the bottom of the deck and the delamination. Progressed delamination (poor condition) 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. This condition is graded as a serious condition and is always in the audible frequency range.

2.3 Concrete Deterioration

While chlorides are usually considered to be the biggest concern for salt induced corrosion, a number of deterioration processes in decks are associated with other chemicals and actions. Those, fro example, 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. Similar deterioration can be caused by repeated freeze and thaw, alkali-slica-reaction (ASR), mechanical stressing, overloading, etc. In all the cases deterioration leads to either reduced mechanical properties or altered electrical/dielectric properties, or both. Ultrasonic surface waves (USW) method will be effective in detecting and measuring changes in mechnical properties, while ground penetrating radar (GPR) will be effective in detecting changes in dielectric properties.

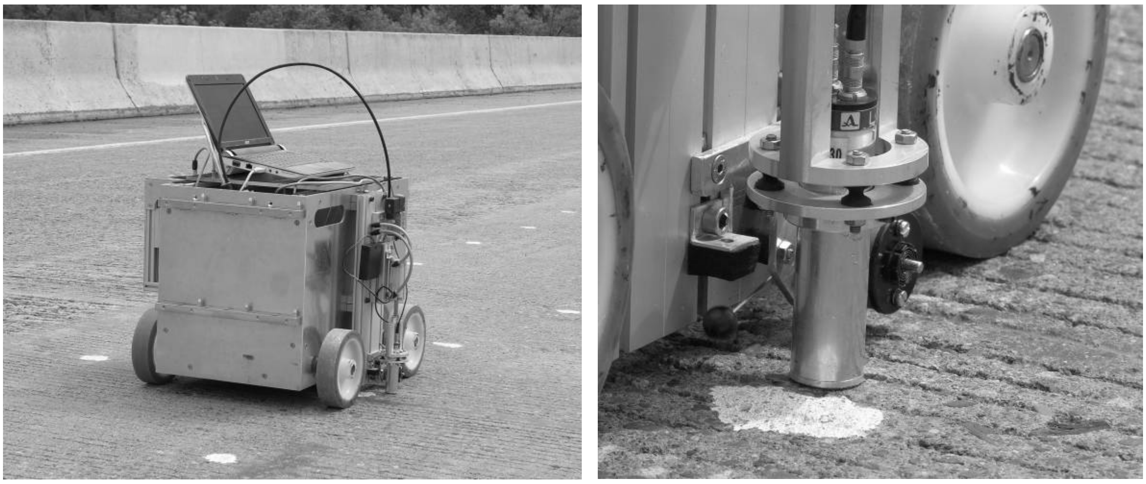

Figure 4. The Stepper (left) and impact echo probe (right).

The objective of the USW test is to measure the velocity of surface waves that can be linked to the concrete elastic modulus. In cases of mostly uniform materials, like concrete in bridge decks, the velocity is fairly constant for a limited range of wavelengths (Nazarian et al., 1993). Therefore, the modulus is obtained from the average surface wave velocity for wavelengths not exceeding the thickness of the deck. Variation in the phase velocity would be an indication of the variation of material properties with depth. Devices like the portable seismic property analyzer (PSPA), shown on the right side of Figure 5, can be used in the evaluation of concrete modulus by the USW method. Variation in concrete modulus in the deck does not necessarily mean deterioration. Such variations can often be introduced at the time of construction, due to material variation and placement procedures. Therefore, only a periodical measurement of changes in the concrete modulus would lead to identification of deterioration processes.

GPR provides a qualitative assessment of concrete deck deterioration through measurement of attenuation of electro-magentic waves on the rebar level. Correlations with impact echo data and ground truth measurements have also shown that GPR has potential for delamination detection in areas of highly attenuated signal. In addition, GPR surveys can provide information about deck thickness, concrete cover and rebar configuration (Romero et al., 2000; Barnes and Trottier, 2000). 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. A GPR survey of a bridge deck using a ground coupled antenna is shown on the left 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. Once the attenuation map is completed, a unique deterioration threshold is established using ground truth, such as cores or NDE methods like impact echo (Barnes and Trottier, 2000; Gucunski et al., 2005) to provide the results interpretation.

Figure 5. GPR with a ground coupled antenna (left) and USW testing using PSPA (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 a bridge deck in Virginia in Figures 6 and 7. The bridge was evaluated as a part of the LTBPP's pilot project. The bridge has about 20 cm (8 in) thick deck on steel girders. The condition assessment from four technologies, namely HCP, ER, IE and GPR, is shown in Figure 6. The USW measurement results are not presented herein for the sake of space. 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. Qualitatively, HCP and ER point to about the same areas as having active corrosion and corrosive environment. This points to a somewhat expected relationship between the corrosive environment and active corrosion. Qualitative similarities to HCP and ER results can be also observed in the GPR results, and to a lesser extent IE results. This should be explained that the likely primary cause of deterioration is corrosion. Still, there are also differences. 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.

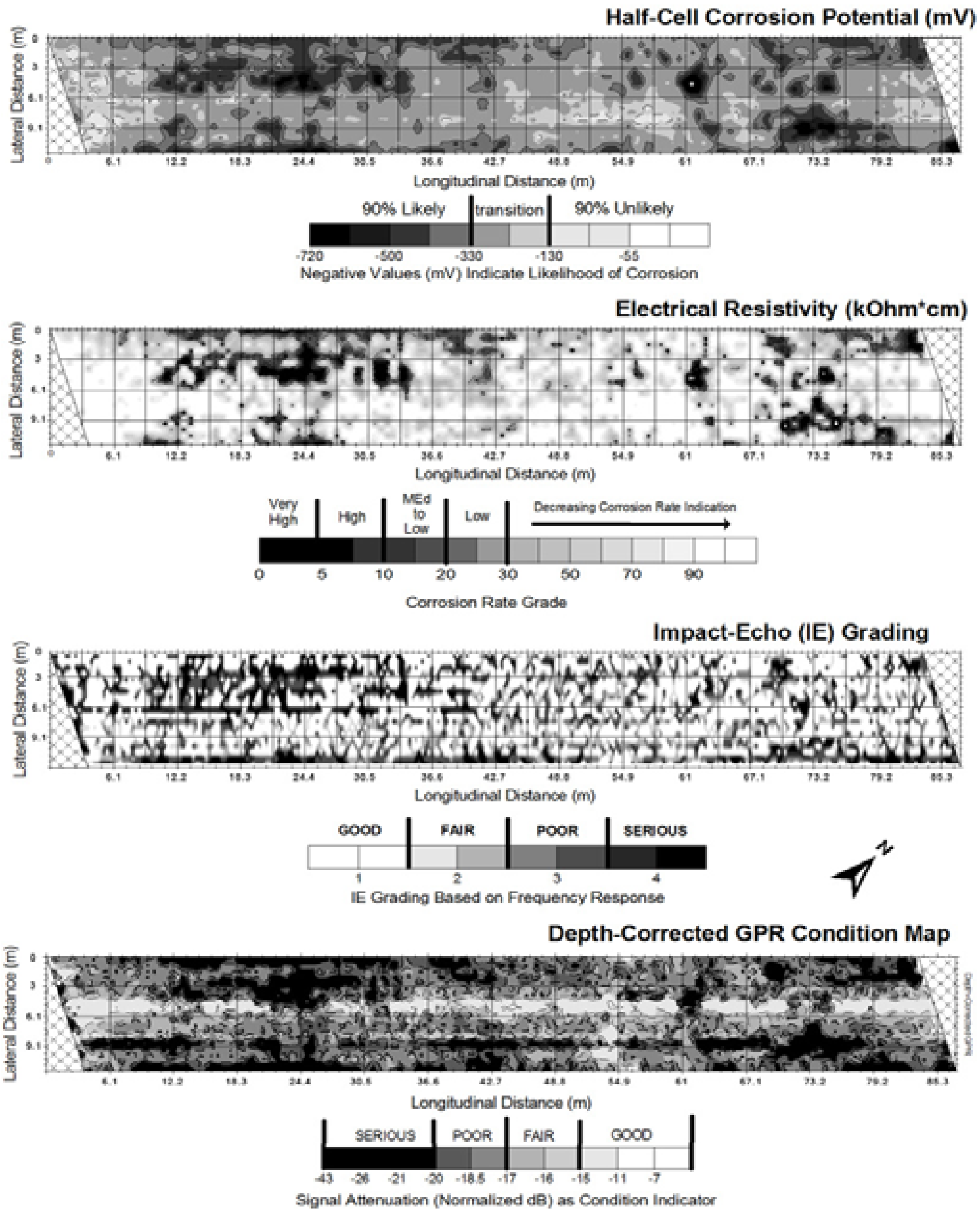

Figure 6. Condition assessment of the deck of a bridge in Haymarket, VA, using HCP, ER, IE and GPR.

Since the results obtained from NDE technologies are quantitative, they can be used to obtain rating, whether of a section of the deck or the deck as a whole. This is illustrated in Figure 7 by the segmentation and rating of the Virginia bridge deck with respect to corrosion from HCP results and delamination from the IE results. The rating is calculated according to the formulas shown in the figure. A summary rating for the deck can be also calculated by assigning different weights to different deterioration types. On the network level such a rating may assist in prioritization of bridges, while on the project level in prioritization of sections of the deck.

4 CONCLUSIONS

Multiple NDE technologies in the condition assessment of concrete bridge decks complement each other in building a complete picture of bridge deck deterioration. In addition, they can point to probable main underlying causes of deterioration. Finally, the quantiative nature of NDE results enables rating of the deck and its segments with respect to evaluated deterioration type, which might assist on prioritization on both network and project levels.

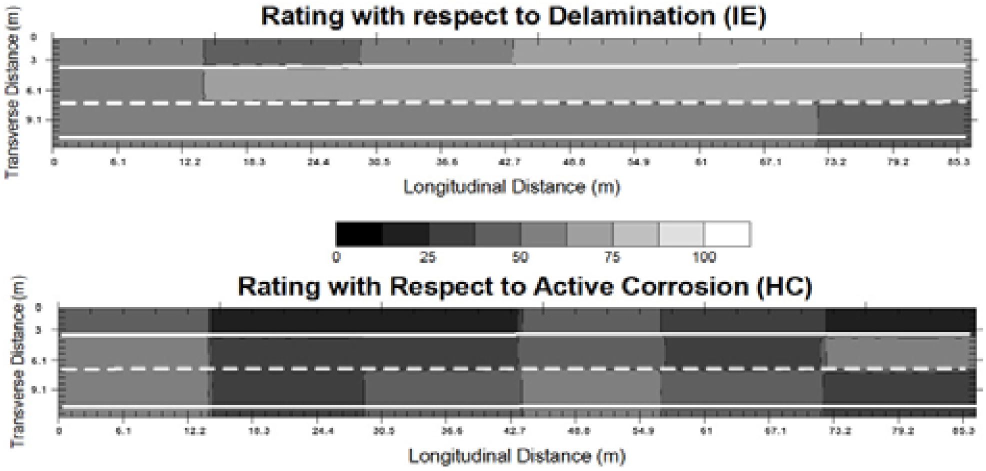

Figure 7. Segmentation and condition rating of the deck based on the HCP and IE results.

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