Journal of Applied Geophysics 97 (2013) 37–44

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A three dimensional approach for tracking cracks in bridges using GPR

Andrea Benedetto

Department of Engineering, University Roma Tre, Via Vito Volterra 60, 00146, Rome, Italy

ARTICLE INFO

Article history:
Received 16 October 2012
Accepted 31 December 2012
Available online 20 January 2013

Keywords:
Bridge deck inspection
Bar corrosion
Ground penetrating radar
Bridge maintenance
3D imaging
GPR signal processing

ABSTRACT

Corrosion associated with reinforcing bars is the most significant contributor to bridge deficiencies. The corrosion is usually caused by moisture and chloride ion exposure. The reinforcing bars are attacked by corrosion and yield expansive corrosion products. These oxidation products occupy a larger volume than the original intact steel and internal expansive stresses lead to cracking and debonding. There are some conventional inspection methods for the detection of the reinforcing bar's corrosion but they can be invasive and destructive, often laborious, and lane closure is required and it is difficult or unreliable for any quantification of corrosion. For these reasons, bridge engineers always prefer more to use the ground penetrating radar (GPR) technique. In this work a novel numerical approach for three dimensional tracking and mapping of cracks in the bridge is proposed. The work starts from some interesting results based on the use of the 3D imaging technique in order to improve the potentiality of the GPR to detect voids, cracks or buried objects. The numerical approach has been tested on data acquired on a bridge by using a pulse GPR system specifically designed for bridge deck and pavement inspection. The equipment integrates two arrays of Ultra Wide Band ground coupled antennas, having a main working frequency of 2 GHz. The two arrays are using antennas arranged with a different polarization. The cracks, associated often to moisture increase and higher values of the dielectric constant, produce a not negligible increase of the signal amplitude. Following this, the algorithm, organized in preprocessing, processing and postprocessing stages, analyzes the signal by comparing the value of the amplitude all over the domain of the radar scan.

1. Introduction

One of the most critical problems that brings about bridge deck deterioration and concrete slab damage and affects the regularity of surface pavement comes from the corrosion of the steel bar reinforcement in bridges.

The corrosion of steel is generally activated by moisture and chloride ion exposure. More in depth the presence of excessive moisture and chloride ions in the concrete adjacent to the reinforcing bars is the main cause of corrosion. In these cases chemical oxidation reactions occur and the steel bars are attacked. Particularly acidic solutions of moisture and chloride, coming from the top of the concrete deck, ingress to the reinforcement steel and contribute to depassivate the alkaline environment in concrete. This is the start of the progressive corrosion. The solution reacts with the steel generating oxidation processes and products such as FeO, Fe_2O_3, Fe_3O_4 and other oxides. In the initial passivity stage these oxides are generated just along the reinforcement bars. Once the corrosion is activated the process progresses very rapidly. The oxides yield expansion and the volume increases. In general it accelerates the formation and development of cracks in all the surrounding concrete.

Meanwhile, because the produced oxides occupy a larger volume with respect to the original intact steel, expansive stresses are generated enhancing and facilitating the increase and diffusion of cracks in the material. In particular we can observe a first phase of debonding between steel and concrete, the delamination of the concrete cover material from the reinforcement and then a rapid phase of cracking, starting from the steel concrete contact to the top layers of the structure (Neville and Brooks, 1987). The cracks generated at the steel cement contact propagate with time to the surface facilitating the water infiltration (Hubbard et al., 2003).

The basic motivation of this paper is to convince that an early detection of the bar corrosion and a full correct tracking of hidden cracks are strategic in order to anticipate the main delamination. It results in a significant reduction of the maintenance costs and in a relevant extension of the life of the bridge and the reinforced structures in general.

For this scope the proposed approach is based on the use of the ground penetrating radar. In fact this electromagnetic tool offers many advantages in the inspection of the bridge deck, the localization of the steel reinforcement bars and corrosion diagnosis. This depends on the fact that there is a relevant contrast among the dielectric characteristic of original materials and oxides as well as among water, steel and concrete dielectric properties (Halabe et al., 1993a; Holt and Eales, 1997). In fact it can be observed that the bridge engineers that prefer to use the ground penetrating radar (GPR) technique rather than traditional inspection methods are always more (Alongi et al., 1993; Benedetto and Pensa, 2006; Chen et al., 1994; Chung et al., 1992; Maser, 1989;

E-mail address: benedet@uniroma3.it.

0926-9851/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jappgeo.2012.12.010

Morey, 1998; Scullion et al., 1994). They report also that it is certainly more efficient and effective (Barnes and Trottier, 2004; Halabe et al., 1993b, 1997; Rhazi et al., 2007). It is not to be neglected that the GPR technology helps greatly in reducing the interferences with traffic while measuring and testing. In fact the work zone results are very temporary and limited in the occupied space along the road lane, so that the data can be acquired rapidly, more safely even during traffic.

Using novel GPR systems with multiple antenna arrays the data can be acquired with an optimal spatial resolution. More in depth the actual tomography that can be generated from the GPR radargram is characterized by a very fine longitudinal resolution that is usually in the order of $10^{-1} \div 10^{-2}$ m and depends on the sampling step adopted during the survey (typically in the order of 10^{-2} m). The lateral resolution depends on the way of operating during the survey and in particular it depends on the distance between two parallel longitudinal scans. This is stated by the operator or, in the case that multiple antenna arrays are used, it is determined also by the distance between two consecutive antennas and it is in general in the order of 10^{-1} m (Barnes and Trottier, 2009; Benedetto et al., 2012; Narayanan et al., 1998).

Basing on the radargram with this level of resolution it is possible to generate an accurate three dimensional tomography. This is a novel source of information to detect and follow the cracks because it permits the correlation of data in a full three dimensional domain. In fact two dimensional radargrams, typically B-scan and C-scan that are respectively vertical and horizontal tomographies in the x–z section and the x–y plane, are not correlated to the third dimension, respectively y and z. On the contrary the availability of a 3D tomography makes it possible to correlate all the data in a full 3D grid and it is consequently possible to follow cracks out of the 2D domain (Di Donato et al., 2010).

The objective of the paper is to formulate, firstly validate and discuss an algorithm for the automatic tracking of bridge cracks in a full 3D domain, basing on a high resolution GPR tomography.

2. Experimental background and evidences

2.1. Instrument

In order to generate a full 3D tomography of the bridge structure an advanced GPR system with a novel array of antennas specifically designed for a bridge inspection has been used. The system is called RIS Hi Bright. This system is efficiently and effectively used for bridge deck and pavement inspection. In general similar systems can measure pavement and concrete thickness, detect moisture and concrete damage, locate slab rebar and pipes (e.g., Benedetto, 2010; Dolgiy and Zolotarev, 2006; Shihab and Al-Nuaimy, 2005; Simi et al., 2012; Utsi and Utsi, 2004). In this work, with the scope of detecting cracks in concrete structures, it has been used to extract accurate 3D tomography of the bridge pavement, concrete slab and any other structural elements.

The system is specifically designed for bridge applications and, for this reason, optimizes the polarization of the array of antennas in order to increase the resolution, thanks to a very dense data collection. At the same time the efficiency of the survey and the safety in the work zone are increased by the system as well as the time needed to perform the acquisition.

More in depth, the equipment integrates two arrays of Ultra Wide Band ground coupled antennas, having a main working frequency of 2 GHz and featuring a very large bandwidth (more than 100% of the main frequency). The high frequency and the large bandwidth permit to reach a resolution of 1.25×10^{-2} m (quarter of wavelength criteria).

Each antenna includes a transmitter, a transmitting dipole, a receiver and a receiving dipole. Basically, each antenna is therefore capable of emitting an EM pulse and collecting the backscattered signal reflected by buried objects. The two arrays within the RIS Hi Bright are using antennas arranged with a different polarization (Simi et al., 2012; Villela and Romo, 2010); in fact, one array includes sensors with parallel polarization with respect to the scanning direction (VV array), the other has sensors in orthogonal polarization with respect to the scanning direction (HH array). Overall the system collects 16 profiles within a single scan (8 HH + 8 VV). The distance between two adjacent profiles is 10^{-1} m only and VV and HH traces are collected over the same line; total scan width is 0.7 m. Fig. 1 shows the system during the survey on a bridge.

2.2. Experimental site and survey procedure

For the validation of the algorithm that will be presented in detail in Section 3, in order to carry out the survey and acquire the necessary data, a bridge over the main road network in central Italy that appears in an advanced damaged condition has been selected.

The first cause of damaging is the weakening of the reinforcement due to the corrosion that is enhanced both by the passing high loads and by the cold weather in the winter season when the bridge is frequently exposed to icing problems. The length of the bridge is 393 m. The estimated traffic volume is very low (less than 1500 vehicles per day) but the percentage of heavy trucks is over 30%. The transversal section of the bridge is 12.4 m wide. The bridge has one carriageway composed by two lanes with different flow directions. The lanes are 3.75 m wide and the shoulders are 1.0 m. Fig. 2 shows the bridge platform.

The bridge is reinforced by longitudinal and transversal bars. The longitudinal bars have diameters of 14 and 80 mm, and the transversal ones 8 and 20 mm. The top asphalt layers over imposed to the concrete slab are 100 mm thick in total, the binder layer is 70 mm thick and the top layer is 30 mm.

The RIS Hi Bright system is dragged at the speed of 3.0 km/h by the operator; six longitudinal scans cover one lane of the road (Fig. 3). In fact, the wideness of the system being 0.8 m, six scans cover 4.8 m that is approximately the wideness of a half carriageway: lane and shoulder.

The productivity of the system can reach about 1000–2000 m^2/h depending on the traffic flow, the operability conditions and the method adopted (e.g., if it is a one way scan or if the GPR acquires data going in one direction and coming back in the opposite direction).

On the top layer some longitudinal cracks are visible close to the center line and at the lane borders (Fig. 4).

2.3. Crack detection

The surface of the bridge has been photographed by using a high resolution camera in order to catalogue all the visible cracks appearing on the top layer of the pavement. The average thickness of the cracks is 5.5 mm, while the length over the surface in several cases is greater than 4 m. The zone of the bridge that appears more cracked is in proximity of the joint.

The diagnosis of the crack by GPR results is controversial. In fact the thickness of the cracks is generally less or comparable to the GPR resolution that depends on the signal wave length (in this case, considering that the signal frequency is 2 GHz and the dielectric permittivity of the dry pavement material is from 4 to 10, the expected resolution is in the order of 20 to 50 mm). So it happens that it is difficult, sometimes impossible, and generally unreliable to deconvolve the signal in order to detect any additional reflection due to the cracks. However the changing of the mean dielectric properties of the materials induced by the presence of the cracks modulates the signal amplitude amplifying it. In effect an increase of the signal amplitude has been observed corresponding to the presence of cracks (Barnes et al., 2010; Benedetto et al., 2012).

Basing on this evidence it is possible to extract the geometry of the cracks automatically from a three dimensional tomography checking the signal amplitude.