AN INVESTIGATION ON APPLICATION OF THE ELECTRICAL RESISTIVITY TOMOGRAPHY METHOD TO CONCRETE STRUCTURES

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1- Overview

Reinforced concrete used for bridge decks and pillars, highways and other transportation facilities experience loss of integrity over time caused by poor initial quality, action of de-icing salts, temperature changes, fatigue and, above all, delamination caused by corrosion of reinforcement bars (rebars for brevity). Electrical resistivity is sensitive to those losses of integrity. Using 3D numerical modeling we first examine resistivity responses associated with those problems. In the case of rebars, differences occur if they are corroded or not and if cracking or delamination is taking place; resistivity anisotropy is also indicative of rebar distribution and concrete integrity. We also investigate the potential of imaging to recover the resistivity distribution. Finally, the technique is applied to the auscultation of two bridge decks in Montreal and compared with other geophysical and geotechnical data.

2- Introduction

The DC resistivity method has been widely used for groundwater prospecting, environmental and engineering problems; however its use in non-destructive testing (NDT) is limited. Cabasut et al (1997) have investigated loss of integrity of water pipes by conducting resistivity surveys inside. Usually the method is slow because of the physical contact of electrodes with the material under investigation. The contact may be difficult to achieve and when concrete is involved special techniques must be use to penetrate the material. Also engineers will rely more on mechanical properties (seismic, sonic methods) than electrical resistivity to diagnose problems. On another hand, non-seismic methods like GPR would be much faster to perform surveys and generally resolve the geometry better. However, we would like to show the potential of the method in the present state and discuss about further developments that could increase its use.

The theory and the basic principles of the resistivity method can be found in reference text books such as Reynolds (1998). From the measure of potential differences generated by a current flowing into the material under test, an estimate of the electrical resistivity can be found. Using various configurations and combinations of electrodes, a three-dimensional (3D) electrical image of the material can be obtained from inversion (Zhang et al, 1995).

In the following presentation, we will use 3D modeling codes of Spitzer (1995) and Zhang et al (1995) and a modified version of the inversion algorithm of Zhang et al (1995).

3- Concepts

Compressive strength of concrete is dependant on the water/cement ratio. The higher the ratio the lower is the strength. Electrical resistivity of concrete decreases almost linearly with increasing water/cement ratio for a given cement content (Neville, 1998) and therefore resistivity can be diagnostic of the compressive strength. Electric current is conducted through moist concrete by ions (electrolytic mechanism). Figure 1 shows the resistivity response with curing time for three concrete slabs. Slabs B30-05 and B30-10 display an observed compressive strength of 24.3 MPa for a concrete mixture of 160 kg water, 350 kg cement (water/cement ratio 0.46), 1060 kg 20 mm aggregates and 830 kg sand. Air is 8%. Slab B15-10 displays an observed compressive strength of 9.2 MPa for a mixture of 160 kg water, 200 kg cement (ratio 0.80) and 950 kg sand. Air volume ratio and amount of aggregates are the same as the previous slabs.

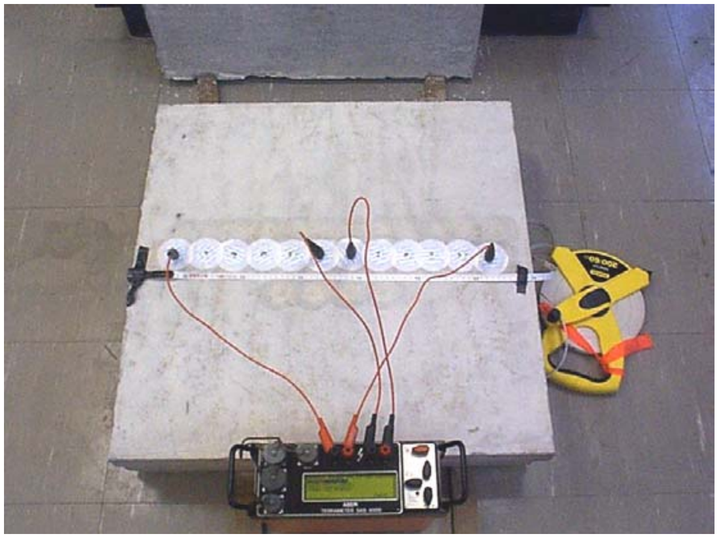

Figure 1a: Resistivity measurements on concrete slabs

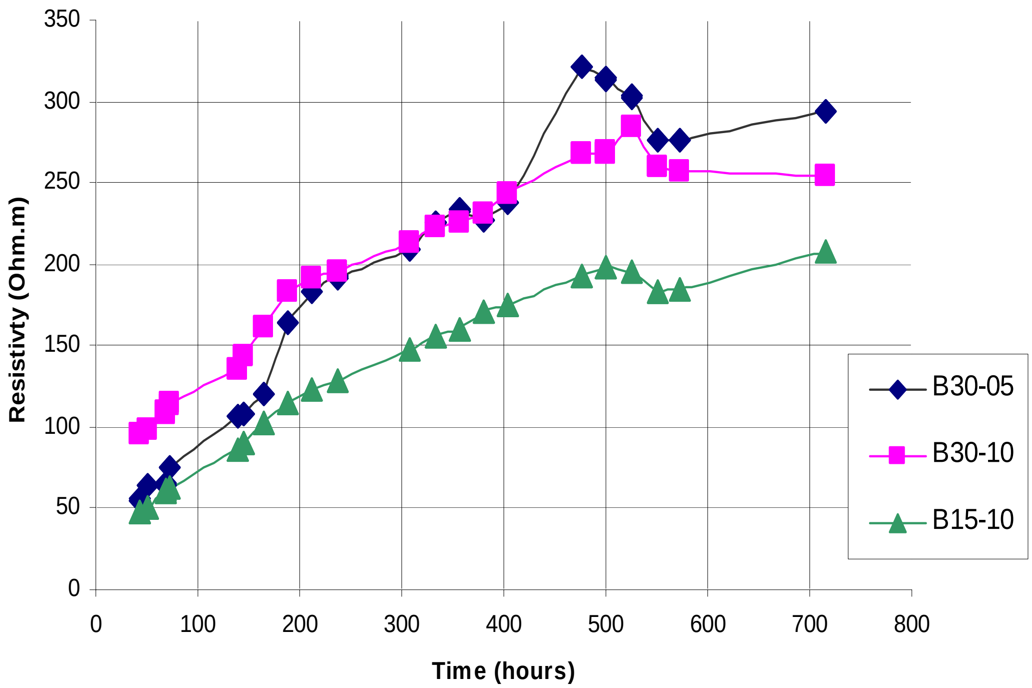

Figure 1b: Resistivity as function of curing time for three concrete slabs; B30-05 and B30-10 have the same compressive strength (24.3 MPa) and water/cement ratio (0.46); B15-10 has a compressive strength of 9.2 MPa and a ratio of 0.80. The Wenner spread is used.

Progress of corrosion of steel reinforcement is controlled by the electrical resistivity of concrete and therefore it is better to maintain high resistivities within the concrete. Addition of chloride ions originating from deicing salts for example will decrease electrical resistivity and accelerate the generation of corrosion.

Experiments have shown that electrical resistivity of concrete is dependant upon its integrity (Cabasut et al, 1997). Damages can vary from cracking, spalling and delamination induced by steel reinforcement corrosion to scaling caused by weathering (frost-thaw). Presence of water or not in the cracks will modify the bulk resistivity of the material.

Therefore, loss of integrity, chloride ions and compressive strength will affect resistivity of concrete and a method based on the mapping of the resistivity distribution will help diagnose defects in concrete structures.

4- Numerical modeling and imaging

In order to provide diagnostic information about the concrete the method must be sensitive to change in concrete integrity. Also, data acquisition must be optimized to yield the needed information and spatial resolution is an important issue. Finally, from the apparent resistivity (or potential) measurements, an electrical resistivity model must be recovered and imaging techniques must be developed.

4.1: modeling of a concrete slab

The model consists of a 30 cm-thick concrete slab that includes or not a row of reinforced bars (figure 2). The resistivity of the concrete is 300 Ω.m; the rebars are modeled as square bars of 0.01 Ω.m resistivity at a depth of 9 cm. The layer containing the rebars may be made resistive to model delamination. Air is given a resistivity of 1000 Ω.m. The X axis is orthogonal to the direction of the rebars; Y axis is parallel. The electrodes are distributed in X and Y with a separation of 10 cm. In this case, we use the pole-pole configuration. Figure 3 shows the apparent resistivity ρ_a computed for all the pairs of transmitter-receiver electrodes. It shows (1) that ρ_a increases with separation and (2) that anisotropy exists. The latter is an excellent example of the electrical resistivity paradox, the resistivity along the rebars being about twice the one across. Now if the layer including the rebars is filled with air to simulate delamination, ρ_a is reduced by about 30% in all directions (figure 4). If the delamination is maintained but the rebars are removed, ρ_a is now isotropic and increases with larger separation (figure 5) because of the finite thickness of the slab in the air.

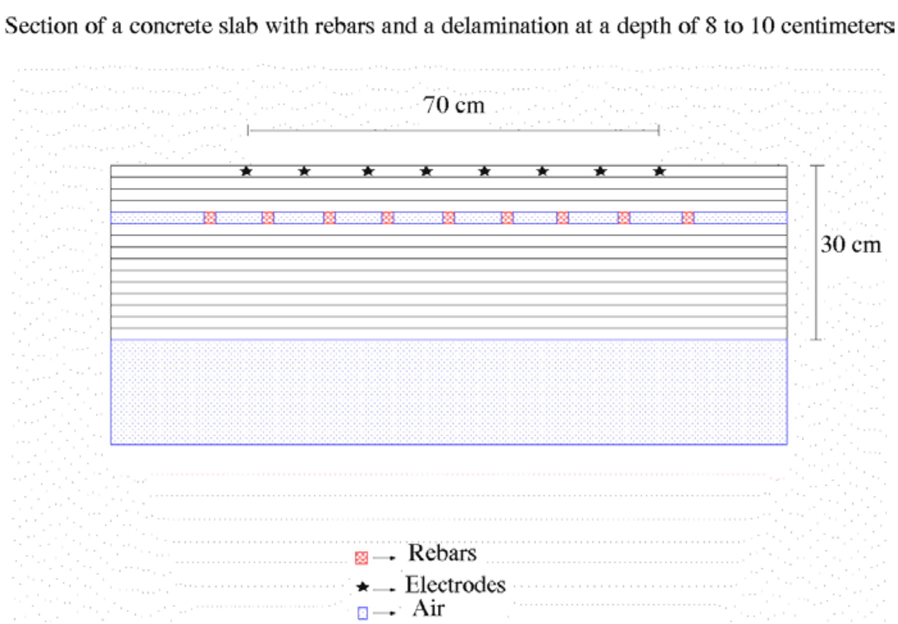

Figure 2: concrete slab model used for the numerical modeling showing the location of electrodes and rebars

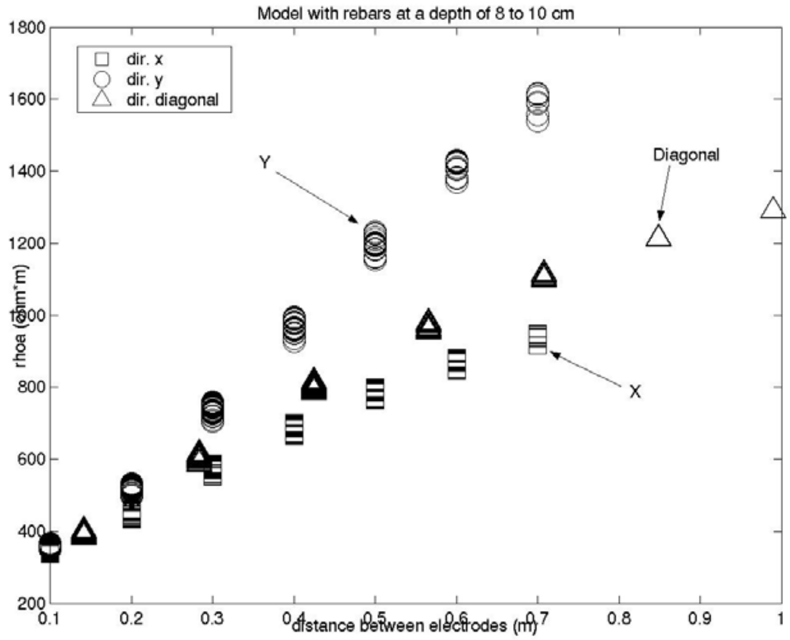

Figure 3: apparent resistivity displayed as function of electrode separation for the concrete slab model with rebars (no delamination) at a depth of 8 cm.

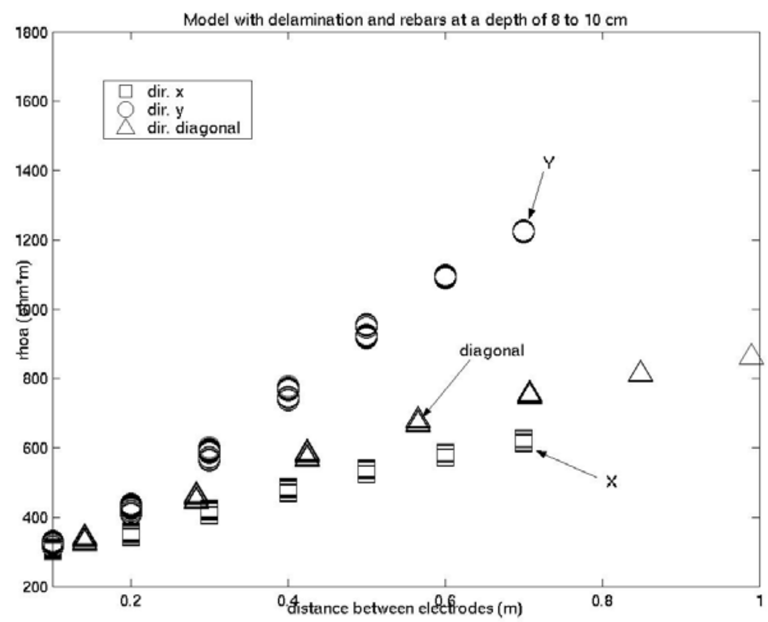

Figure 4: apparent resistivity displayed as function of electrode separation for the concrete slab model with rebars and delamination at a depth of 8 cm.

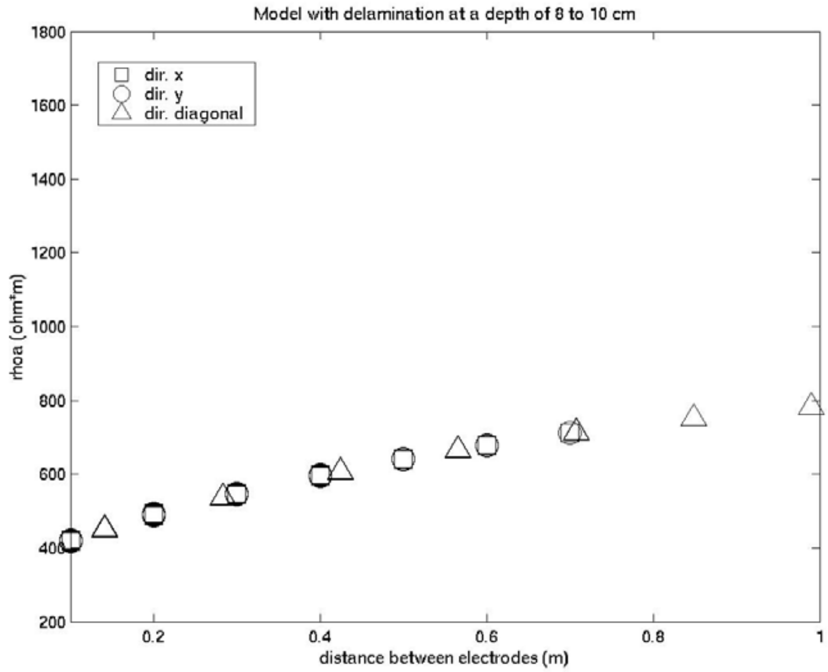

Figure 5: apparent resistivity displayed as function of electrode separation for the concrete slab model with delamination (no rebars) at a depth of 8 cm.

4.2: imaging

Figure 6 shows the model resulting from 3D inversion of the modeled data in figure 3. The resistivity of concrete and the depth to the rebars are well determined. The rebar layer appears as a conductive zone with thickness much larger than the diameter of the rebars. This is caused by the intrinsic lack of resolution of the resistivity method and to the smoothness constraint used in the inversion algorithm. The inversion has also recovered the direction (Y axis) of rebars (figure 7).

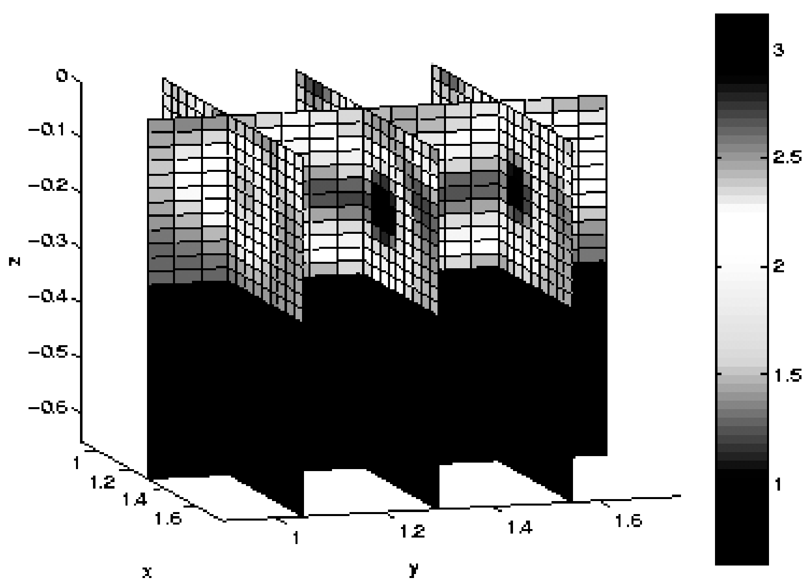

Figure 6: inverted 3D model of data from figure 3. Note that the concrete resistivity and the depth to the row of rebars have been recovered; however location of individual rebars is not resolved.

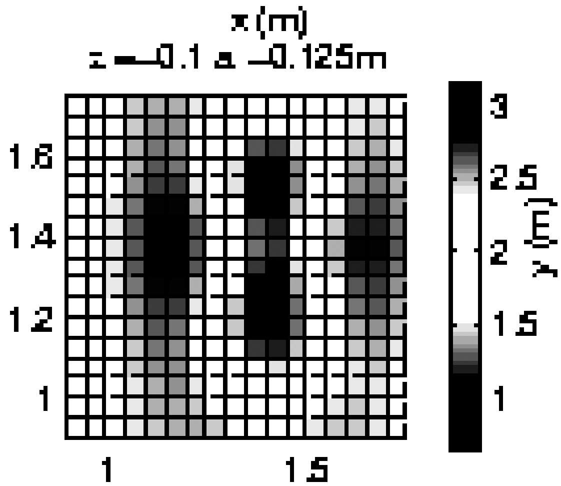

Figure 7: the orientation of the rebars (Y axis) is retrieved from inversion.

5- Applications

Two resistivity tomography surveys have been performed, one on an overpass, the second on reinforced concrete slabs to replace part of a bridge deck.

The Dickson overpass in Montreal had to be destroyed. It had been repaired many times and the concrete structure was considered too unsafe. The City has encouraged researchers and service companies to use it as a test lab for NDT and other techniques. GPR, microseismic refraction, infrared thermography surveys, sonic and seismic tomographies and half-cell measurements were carried out. Concrete samples were also collected from boring, examined for alteration and tested in the lab for the residual compressive strength. Preliminary visual inspection followed by coring and half-cell measurements has helped delineate zones of low and high quality concrete. Pole-pole E-scan type of surveys were carried out using 10 cm electrode separation. The inverted images show good correlation between the resistivity model and the known position of rebars and quality of concrete.

The Jacques-Cartier Bridge is an old structure, vital to the traffic between the island of Montreal and the south shore. In order to reduce traffic annoyance, the concrete deck of the bridge is cut and replaced gradually by prefabricated reinforced concrete slabs. Those slabs are made by a company near the south end of the bridge. The geometry of the reinforcement framework, the geometry of the slab and the composition and mechanical properties of the concrete are controlled and well known. To test the method we have made measurements over one of the prefabricated slabs using various dipole-dipole combinations. Data were collected over three lines separated by 20 cm; electrode separation was 5 cm for 21 electrodes on each line (figure 8). Figure 9 shows the location of the electrodes with reference to the rebars network closer to the surface (~5 cm). A 1.5 GHz GPR survey was also performed over the same investigated zone (figure 10) to correlate electrical properties with the resistivity tomography data and to precisely position the rebars with regard to the resistivity survey. Figure 11 shows one of the GPR profiles recorded across the resistivity lines. The diffraction patterns from the rebars are clearly displayed. Data inversions line by line or all together clearly delineate the first level of rebars and even each rod has a marked anomaly associated with it. The resistivity of the concrete is also well resolved and shows, as anticipated, values for a good quality concrete.

Figure 8: Resistivity tomography over the slab

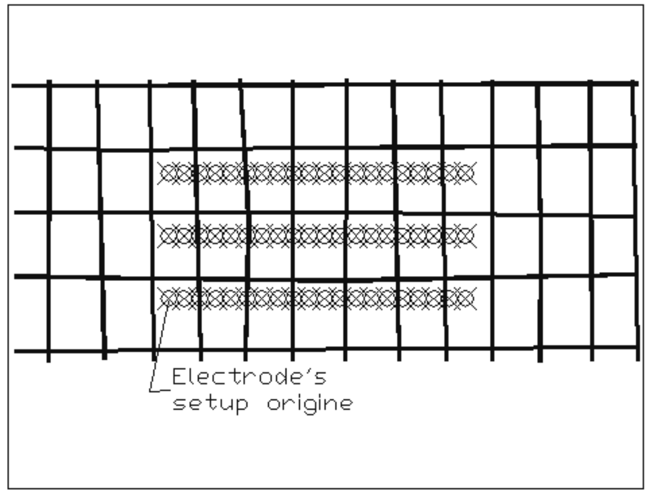

Figure 9: electrode location with regard to the rebar network

Figure 10: 1.5 GHz GPR survey

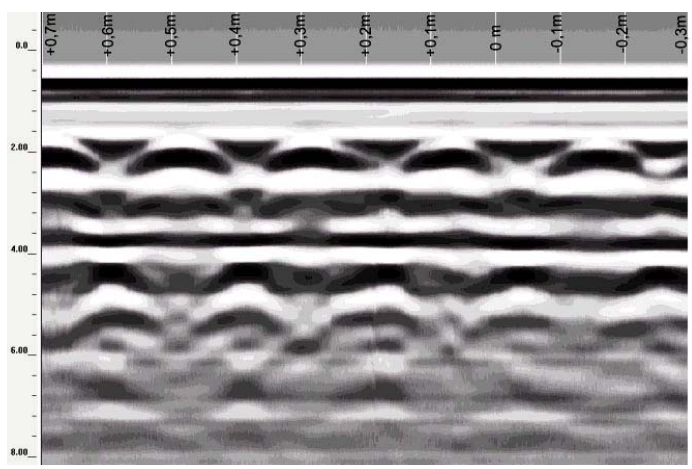

Figure 11: GPR section across the resistivity lines

6- Discussion

When operated in a static mode (electrodes in contact with the structure under investigation, the resistivity tomography leads to excellent estimates of the concrete thickness over the rebars. With special attention, each individual rod can be mapped. The resistivity of the concrete alone can be indicative of the integrity (and residual compressive strength) of a concrete structure.

We have not presented in this paper some aspects in detail. For example modeling tests have been carried out with two superimposed layers of rebars or meshes in the concrete slab. We have also investigated the effect of gradual corrosion of the rebars on the monitored resistivity. Actually the method is sensitive to the state of corrosion and if the method can be adequately applied to NDT, it would lead to preventive diagnostic before corrosion is to severe as to cause delamination. Also, mapping of small amount of chloride contamination (de-icing salts) can be easily done.

The acquisition of 3D resistivity tomography is impaired by the physical electrode contact with the material and the time to record all the possible combinations. In terms on configuration, the dipole-dipole is more appropriate than the pole-pole since it displays more spatial resolution and it is difficult on any structure to set the “infinite” electrodes to some reasonable distance form the survey area.

If the method is to be used for routine transportation infrastructure testing, the measurements have to be made continuously at some speed, acquisition time must be drastically reduced (spatial integration), non-contact (capacitive) electrodes must be employed and a pseudo-real time continuous imaging method must be developed. Towing sets of dipole spreads in parallel behind a vehicle is feasible. Systems such as the OhmMapper (Geometrics) and Corim (IRIS) are commercially available and therefore the technology exists. What must be addressed then is the optimal compromise between electrode configuration, spacing and data correction and imaging.

7- Summary

Electrical resistivity of reinforced concrete is dependant on (1) the intrinsic quality of concrete (composition, compressive strength), (2) the condition of surface/bulk deterioration caused by cracking, delamination and salts, and (3) the distribution of reinforcement bars within the concrete structure. Using numerical modeling, we have shown that the resistivity method is sensitive to the contact existing between the rebars and the concrete, possibly allowing the determination of delamination at an early stage. Imaging techniques using 3D inversion are capable of yielding the resistivity model of the structure under investigation and from there helping diagnose possible damage. Experiments on two bridge decks show that the method is applicable; however a new generation of NDT equipment needs to be developed to expedite surveys over transportation structures.

8- References

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