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Detection of anomalies in bridge waterproof membrane using artificial intelligence applied to GPR

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ABSTRACT

Evaluation of bridge deck waterproofing membrane is essential to assess the durability of the whole structure from the surface (pavement) to the subsurface (bridge structure). Maintenance, rehabilitation and redesign strategies require road surface information for decisive actions by profound analysis. The objective of this project is to develop an innovative 3D electromagnetic mapping showing accurately water leakage in concrete layers of the bridge deck.

Non-Destructive Testing (NDT) can detect critical damages that cannot be detected using visual inspection. In this scope, due to their sensitivity to water content, Electromagnetic waves, especially Ground Penetrating Radar (GPR) may provide a strong means to evaluate the safety and reliability of a bridge.

The aim of the present work is to detect and characterize water leakage in a concrete bridge deck using detailed analysis of the radar signal from a Stepped-frequency Radar (SFR). We use an approach based on the coupling between the Full-Waveform Inversion (FWI) and a supervised learning method applied in local and global approaches to C-scans, obtained at first from SFR output data modelling.

INTRODUCTION

Non-Destructive Testing (NDT) is usually implemented to address specific forms of deterioration or damage during in-depth inspections or special inspections that are conducted as a result of visual findings from routine inspections. Concrete bridge decks that are deteriorating may have NDT performed to prioritize repair activities or better define future periodic needs. In some cases, NDT can detect critical damage that cannot be detected using visual inspection.

Electromagnetic (EM) methods are mostly interesting, because they are sensitive to water content changes. Besides, these methods can give us both physical and geometrical information. Ground-penetrating radar (GPR) based on EM wave propagation, is a rising non-destructive technique for measuring the dielectric and geometric characteristics of materials. It is a common technique for geometrical applications (rebar detection, road thickness estimation, debonding detection etc.) in the civil engineering domain, and study for material characterization (water in concrete, asphalt).

The objective of this work is to detect and characterize water leakage in a concrete bridge deck using detailed analysis of the radar signal. Fig. 1 presents a suggestive approach combining the use of GPR technology combined with a Full-Waveform Inversion [1] to achieve our goals.

A second approach complementing the general method from Fig.1 is proposed, starting from a calibration methodology for the estimation of durability indicators of the auscultated structure, using machine learning (ML) methods as an artificial intelligence processing method [2].

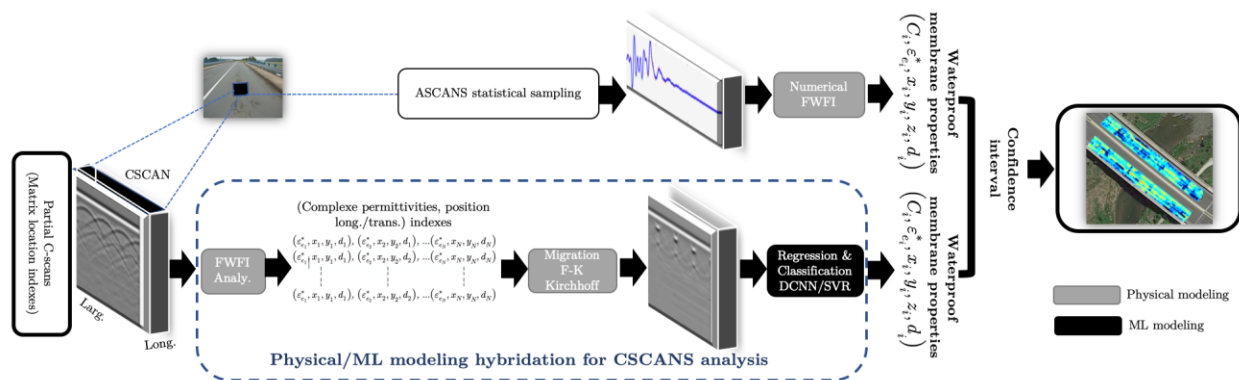


Figure 1: ML / FWI hybridation global process for automatic detection, localization and classification of defects in waterproofing membranes

Therefore, in this paper we present a numerical study in order to evaluate the ML method through testing on **synthetic (modeled with GPRMax)** concrete bridges with the Gaussian distribution of dielectric permittivity in concrete layers.

METHODOLOGY

The characterization of the state of a waterproofing membrane (presence of water or not under the screed, location and extent of the problem) is carried out using Stepped-Frequency Radar (SFR) technology and Ultra-Wide Band antennas. This makes it possible to obtain the quantitative information of the materials under test, in terms of thickness and EM characteristics (*i.e.* permittivity). The objectives of this paper are conducted in two phases.

During the first phase, an innovative Full-Waveform Inversion (FWI) approach using 3D Finite-Difference Time-Domain (FDTD) forward-modeling program to estimate object parameters [1] is adopted here. A modified extension of the Nelder-Mead method using Shuffled Complex Evolution (SCE) [3] has been developed to optimize the model parameters. After performing a numerical parametric study, we have proved that the method allows us to restore with good accuracy all the parameters of the structure according to the temporal signal (A-scan), including the dielectric permittivity of concrete. In consequence, we can determine whether the concrete is wet or not. It is considered that the FWI was performed for a 2D model using the method described above.

In the second phase, the research is focused on the application of the supervised machine learning method namely Support Vector Machines (SVM) to locate the defects (position, depth) at different measurement configurations and radar technologies. The distinction is made between the approach based on the analysis of a 1D signal (*i.e.* A-scan) and based on the analysis of a 2D signal (*i.e.* B-scan).

The following section is developed to perform a second approach, using a parametric study based on application of Machine Learning method on detection defaults in Waterproof Membrane (WPM) of concrete bridges.

NUMERICAL VALIDATION

There is an example of results of the machine learning approach implementation for the automatic detection, location and classification of defects in waterproof membrane (WPM) for a few synthetic cases of bridge decks. We considered the hypothesis concerning the physical dependence between degradation conditions of WPM and its dielectric characteristics. In case of water leakage, dependence appears due to variation in complex permittivity at the level of the concrete layer below WPM. Due to the lack of experimental data, we have performed the initial validations with numerical SFR data (A-scans in various configurations) created using the numerical code FDTD gprMax.

Based on the bivariate normal distribution law, models of bridge decks with Gaussian distribution of permittivity in the concrete layer were generated as close as possible to the ground truth. Selection of the attributes of the generated time signals was used for the classification of the GPR-SFR signatures. We distinguish between local and global attributes. The local attributes describe the signal through dielectric characteristics (*i.e.* real and imaginary parts of the dielectric permittivity inverted by the FWI) and geometric (*i.e.* depth, thickness) at the interface of the bridge structure where WPM defect occurs.

The parametric study presented in this work corresponds to an auscultation of six bridge decks with healthy and degraded areas in terms of waterproofing (Fig. 2) with the following parameters:

1. Training database size: 21875 A-scans
2. Test database size: 4160 A-scans
3. Central frequency of the antennas studied: 4 GHz
4. Signal to noise ratio (SNR): 15 dB
5. Dimension of the bridge deck: 50 m x 5 m

Meanwhile, the learning is only done on the raw SFR signals (A-scans) and the annotation of the attributes is done manually once at the very beginning of the training phase for optimization of hyper-parameters. For *in situ* testing, raw SFR synthetic signals are necessary and sufficient to obtain the result of 3D default mapping.

The performance of the methods is quantitatively evaluated from the signal classification results of each A-scan, either in good detection (true positive: TP – 96.84 %), absence of defects (or true negative: TN - 95.83 %), false alarm (false positive: FP - 3.16 %) and non-detection (false negative: FN - 4.17 %). These values are used to establish Receiver Operating Characteristics (ROC) curves and to compute the performance indexes of Dice score (DSC) and Matthew's Correlation Coefficient (MCC).

We have noticed, from the results of Fig. 3, that this hybrid method applied to the GPR-SFR data allows a cartographic representation of the extent and depth of the WPM defect. Besides, despite significant reduction in the size of the training bases, performance remains acceptable.

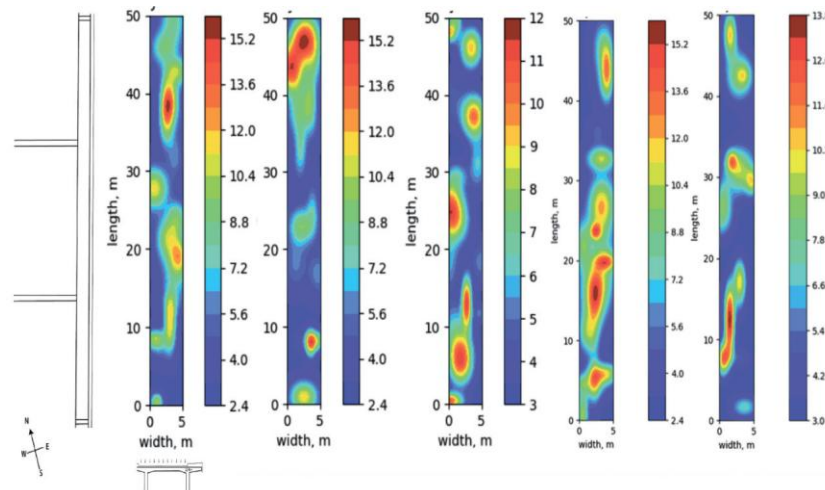


Figure 2: Example of WPM defects distribution for different SFR auscultation cases on independent models of bridge decks

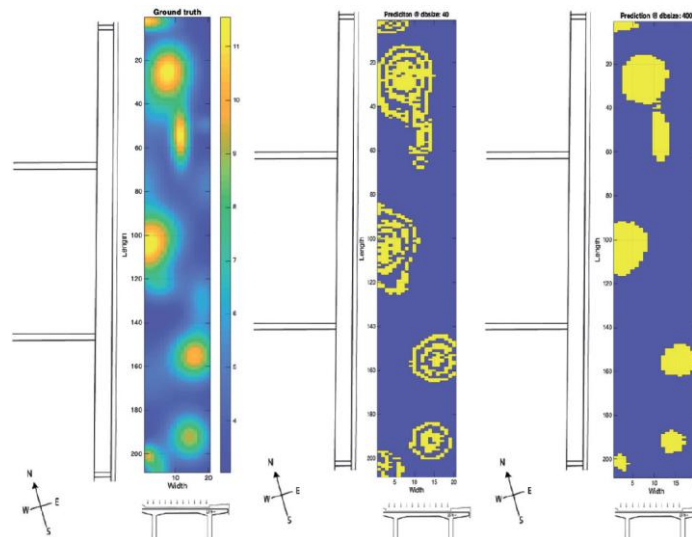


Figure 3: a) (left) Example of distribution of WPM defects for the case of SFR auscultation on a bridge deck test model and results of 3D mapping for the Machine Learning process applied to raw SFR signals with the base of learning of b) (middle) 40 A-scans c) (right) and 400 A-scans.

CONCLUSION

In this article, a numerical FWI approach was used in conjunction with SFR to detect and characterize water leakage in concrete bridge decks. This allows us to define geometric and electromagnetic characteristics of the stratified medium in structure.

In addition, some preliminary numerical results of the second approach were also illustrated, based on the calibration methodology for the estimation of durability indicators of the medium examined by Supervised machine learning methods.

In perspective, the performance evaluation of SVM/SVR methods and the DCNN methods will be performed on *in situ* measurement experiments.

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