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# Optimized full-waveform inversion method for characterization of the waterproofing membrane in bridges

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**Abstract**—The purpose of this article is to present an Ultra-Wide Band GPR (ground-penetrating radar) technology in combination with an improved simplified Full-Waveform Inversion (FWI) approach for evaluation of bridge deck waterproofing membrane. gprMax model is used as a numerical forward model applied on various case studies corresponding to experimental configurations made in the laboratory.

FWI has been designed and simplified for the 2D model. The structure under consideration is one-dimensional.

This study have proved that the method is applicable to various multi-layered media configurations (various materials and structures). In this problematic, the FWI approach allows to evaluate and monitor the required dielectric and geometric parameters of the structure from a temporal signal (A-scan) with high accuracy and less time consuming. This punctual evaluation is needed for the next processing step, that is not discussed in this paper, based on Machine Learning method to detect automatically defects in bridge deck waterproofing membranes.

**Keywords**— GPR (ground-penetrating radar), NDT (non-destructive techniques), FWI (Full-Waveform Inversion), bridge waterproofing membranes

## I. INTRODUCTION

The target of the whole project is to characterize and automatically detect water leakage in concrete bridge decks using Stepped-frequency Radar (SFR) data.

NDT (non-destructive techniques) are implemented to address specific forms of deterioration or damage during in-depth inspections and their observables are used as a priori information for the inverse problems.

Electromagnetic (EM) techniques are mostly interesting, because they are sensitive to water in propagation media. Moreover, these techniques associated to specific processing methods allow the extraction of geometrical information relied to the propagation media. GPR based on EM wave

propagation, is a rising non-destructive technique for measuring the dielectric and geometric characteristics of materials.

In a previous work, we presented a numerical validation of the machine learning method for the detection of damages in waterproofing membrane (WPM) on simulated bridge decks by estimating dielectric permittivity of concrete [1] (Fig.1).

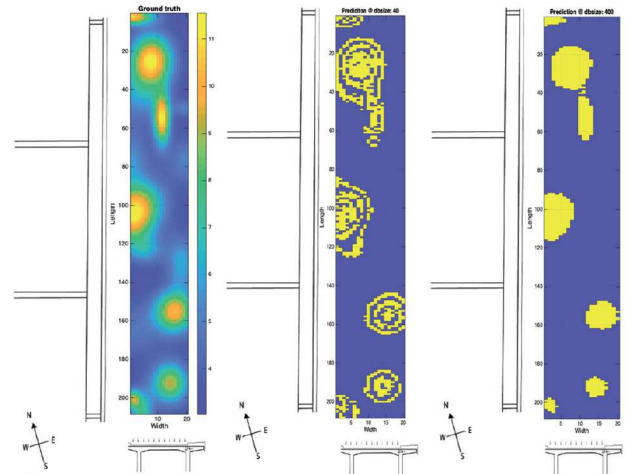


Fig. 1. a) (left) Example of distribution of WPM defects for the case of SFR auscultation on a bridge deck test model and results of 3D mapping for the Machine Learning process applied to raw SFR signals with the base of learning of b) (middle) 40 A-scans c) (right) and 400 A-scans [1].

Now, in order to optimize the characterization of the dielectric permittivity of the aimed layer, it is necessary to perform the FWI approach in order to confirm punctually the confidence degree of the machine learning method results.

The considered method contains at the first stage the GPR technology acquiring data that are processed punctually using a simplified FWI method. This approach makes it possible to extract the dielectric and geometric parameters of a multilayer

structure of concrete bridge decks representing the aimed real configurations.

This paper will focus on presenting an optimized FWI method using experimental data obtained under laboratory conditions.

## II. METHODOLOGY

An innovative FWI method, that is based on a full-waveform finite-difference time-domain (FDTD) forward-modeling program to estimate object parameters [2], was optimized to detect water leakage in the concrete layer of a bridge structure. The forward model is made numerically with software gprMax [3]. The primary steps of the approach are demonstrated in the FWI flowchart (Fig. 2).

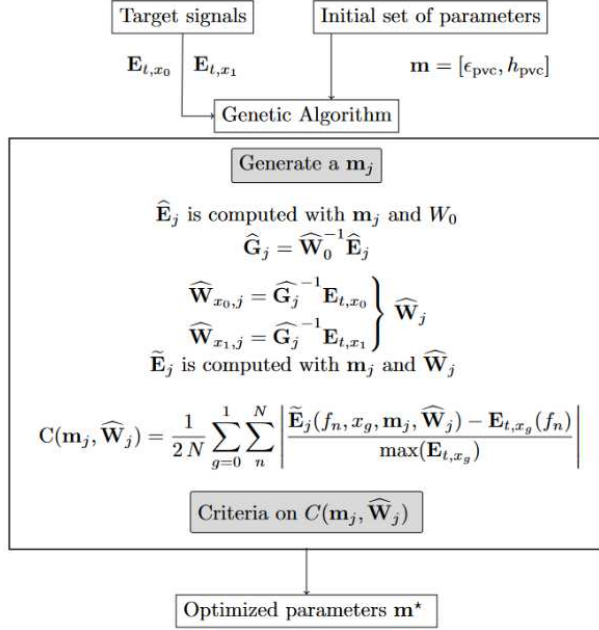


Fig. 2: The FWI flowchart, where  $\hat{X}$  – estimated parameter,  $m$  – arbitrarily set parameters,  $G$  – Green's function,  $x_1, x_2$  – the distance between receiver and transmitter

This procedure is based on simultaneous optimization of the model and estimated source wavelet  $\hat{W}_0$ , in which the forward modeling is performed by the FDTD electromagnetic simulation tool gprMax2D [2, 3].

Based on the approximated parameters ( $\epsilon_{pvc}$ ,  $h_{pvc}$ ), the estimated wavelet  $\hat{W}_j$  is extracted for each point of the genetic algorithm  $j$ . This wavelet allows to obtain immediately  $\hat{E}_j$  that is, the A-scan that this point gives. Then, a comparison of  $\hat{E}_j$  with the experimental A-scan  $E_t$  is done with a minimization of the cost function  $C(m_j, \hat{W}_j)$  using genetic algorithm [4].

For  $\hat{W}_j$  and to combine the data obtained from the wavelets with different distances between receiver and transmitter  $\hat{W}_{x_{0,j}}$  and  $\hat{W}_{x_{1,j}}$ , the weighted average is applied:

$$\hat{W}_j = \frac{\hat{W}_{x_{0,j}}^2 \cdot \hat{W}_{x_{1,j}} + \hat{W}_{x_{1,j}}^2 \cdot \hat{W}_{x_{0,j}}}{\hat{W}_{x_{0,j}}^2 + \hat{W}_{x_{1,j}}^2} \quad (1)$$

To optimize the parameters, the shuffled complex evolution (SCE) [5] is applied. It was extended with the Nelder-Mead method approach and modified by looking for a random point (called “mutant point”) and, every few cycles of evolution,

replacing the worst points with random points in the amount of 33%, which considerably rises the probability of reaching a global minimum. Thus, it let not to get stuck in the local minimum and obtain a global minimum [4].

In the process of adapting full-wave inversion based on the separation of amplitude and phase parameters [4], it was studied that in the case of a homogeneous multi-layered structure, the effect of changing the amplitude and phase parameters of the sandwich on A-scans is insignificant. In view of this, amplitude and phase optimization are not required. This allows only one cycle for the entire execution, without refining the estimated wavelet. This execution takes (relatively) more time, but a response is get in just one cycle, guaranteed.

The new algorithm works faster, since there is no need to refine the estimated wavelet. The wavelet for each point is different, and is immediately found.

## III. EXPERIMENTAL VALIDATION

To validate the optimized FWI method, the simplest case of a single-layer structure with 7 cm thick PVC and a metal plate, created experimentally in laboratory conditions using Ultra-Wide Band antennas [0.4 – 8 GHz], was considered.

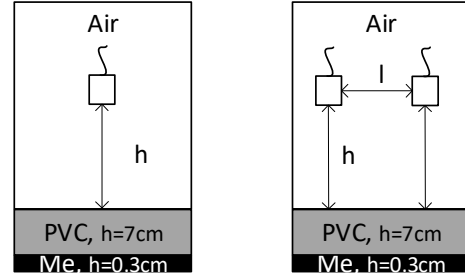


Fig. 3: A single-layer structure with 7 cm thick PVC and metal plate, where  $h = 14$  cm and  $l = 25$  cm for a) (left) mono and a) (right) bistatic antenna configurations

As a target model, two A-scans are obtained using mono and bistatic antenna configurations (Fig. 3) and after applying a calibration procedure (subtraction of air signals from full A-scans).

An experimental setup with the test material is shown in the Fig. 4.

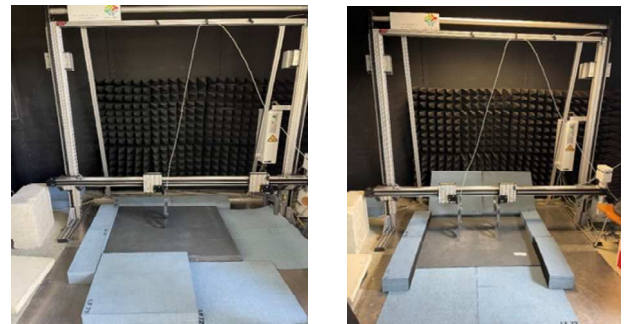


Fig. 4: Laboratory robotic system with a) (left) mono and b) (right) bistatic antenna configurations

As an example, experimental A-scans with a monostatic antenna configuration before and after calibration of the target signal are considered in Fig.5.

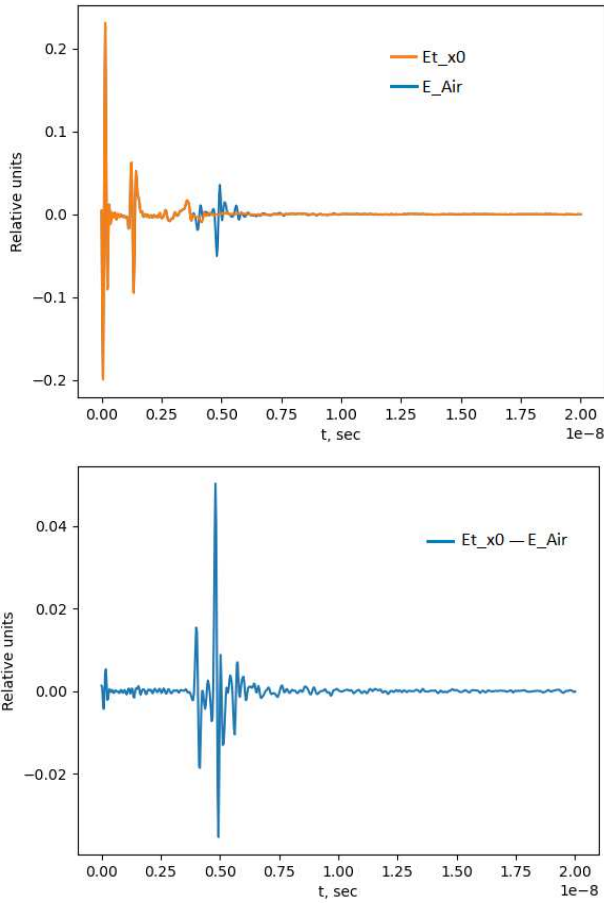


Fig. 5. Experimental temporal signals with a monostatic antenna configuration a) (upper) before and b) (lower) after air subtraction from the target signal

To carry out the FWI method, the variable parameters are the following: PVC dielectric permittivity and thickness.

In addition, noise smoothing was carried out in order to obtain more accurate calculation results. It is a defining procedure for getting correct results.

To integrate the input data, noise smoothing methods such as Moving Average and Hann function are used.

The results of the targeted temporal signals before and after noise smoothing are illustrated in Fig. 6 and Fig. 7.

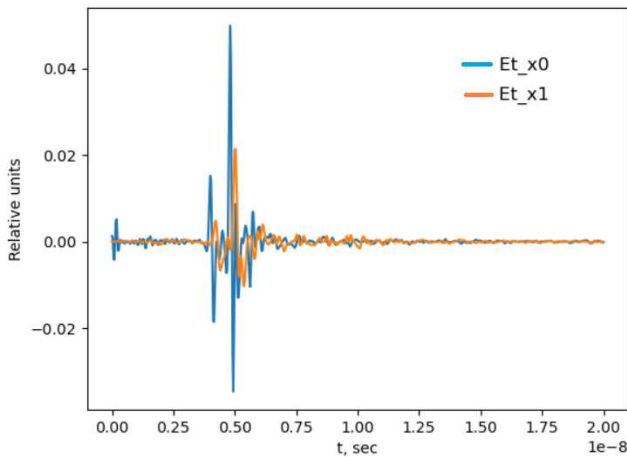


Fig. 6. Targeted A-scans with the A-scan getting from mono and bistatic antenna configurations

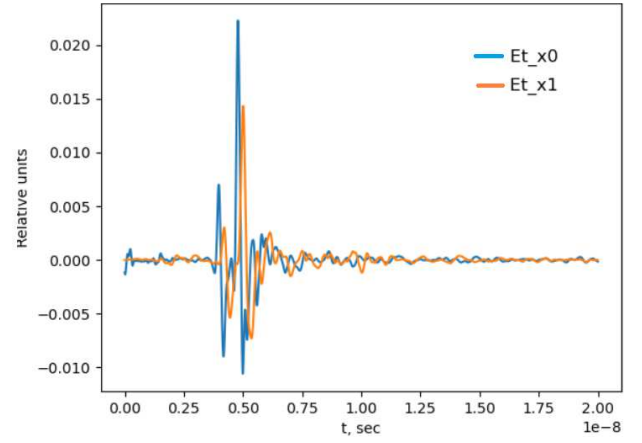


Fig. 7. Targeted A-scans with the A-scan getting from mono and bistatic antenna configurations after noise smoothing

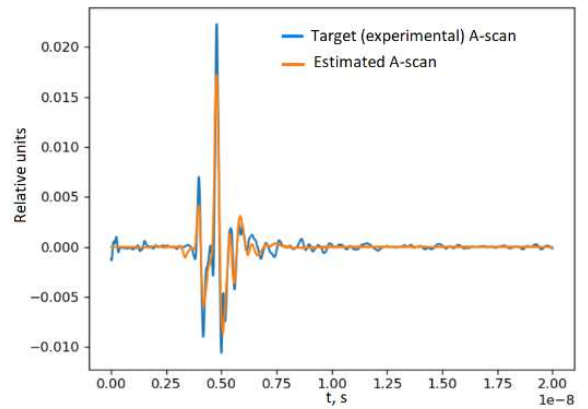
The FWI results corresponding to this experimental study are presented in Table 1.

TABLE I. THE RESULTS OF THE FWI EXPERIMENTAL STUDY

Target parameters	Initial range of parameters	Obtained parameters
$\epsilon_{pvc} = 2.7$	$\epsilon_{pvc} = 1 : 4$	$\epsilon_{pvc} = 2.5$
$h_{pvc} = 70 \text{ mm}$	$h_{pvc} = 30 : 140 \text{ mm}$	$h_{pvc} = 75.8 \text{ mm}$

Fig. 8 shows a comparison between the experimental A-scan and the inverted A-scan (corresponding to the obtained parameters in Table 1).

Targeted and estimated A-scans of the monostatic antenna configuration



Targeted and estimated A-scans of the bistatic antenna configuration

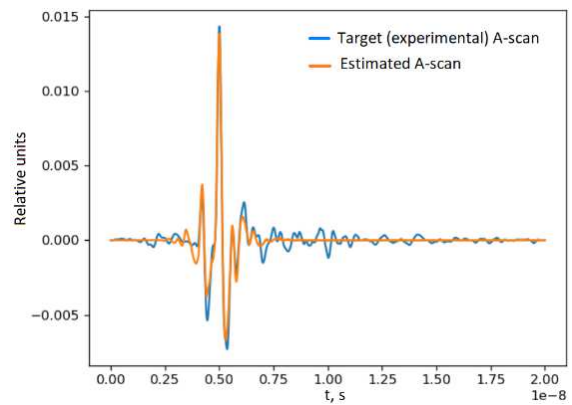


Fig. 8. Targeted and estimated temporal signals of a) (upper) monostatic and b) (lower) bistatic antenna configurations

The graph of the cost function with the indication of the global minimum is presented in Fig. 9.

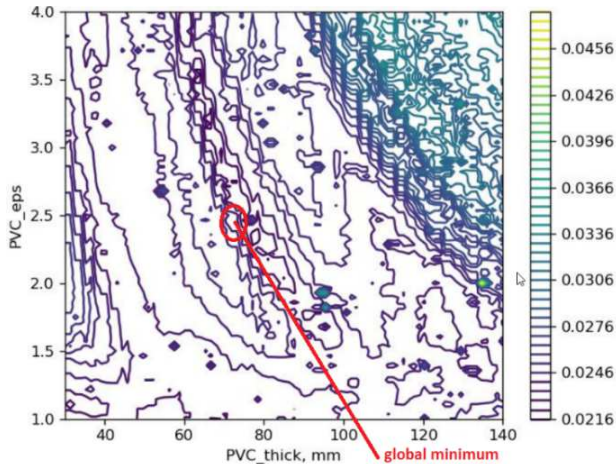


Fig. 9. The graph of the cost function for the case of considered single-layered structure

It can be noticed that the temporal signals obtained as a result of the FWI method match relatively well with the target A-scans. However, the calculation error remains quite large. Currently, methods are being developed to better reduce noise in order to obtain more accurate values in calculations.

#### IV. CONCLUSION

This preliminary study have proved that the newly optimized FWI method using only simultaneous optimization allows to restore the required structure parameters from the temporal signals with high accuracy, as well as reduce the calculation time due to the absence of steps in the algorithm to refine the estimated wavelet.

At the present time, extended experimental campaign is carried out to put the optimized FWI approach into practice. The results will be presented at the current conference.

Moreover, a global approach is being implemented based on the combination between FWI and Machine Learning methods for weaving whether concrete is wet or not following a dielectric threshold.

In this case, with the help of FWI method, it will be possible to determine the dielectric permittivities of the asphalt and waterproof membrane, while fixing the geometric parameters of these layers. Then the two-class Support vector machine (SVM) method determines the state of the concrete: wet or not. Further, with the help of Support vector regression (SVR), concrete moisture content could be rigorously estimated.

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