Current Trends in Non-destructive Testing of Reinforced Concrete Structures using GPR

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ABSTRACT: Since about 20 years, Ground-Penetrating-Radar (GPR) has been applied for the inspection of reinforced concrete (rc) structures. Two-dimensional data acquisition, processing and interpretation were and are mainly used for obtaining structural information such as layer thicknesses or positions of fixtures, such as tendon ducts. Many of those applications are today considered as routine applications of the GPR method and are widely used in practice.

In recent years, advanced GPR techniques such as 3-D data acquisition and processing, data fusion merging information from different antennas and inversion methods have been developed and implemented for the inspection of rc-structures. Also, material properties such as humidity or chloride content have been investigated in addition to the traditional study for structural information.

This paper describes the main features of advanced inspection methods. Benefits and limits are discussed with the help of case studies.

Keywords: Ground-Penetrating-Radar, Non-destructive testing, advanced methods, microwave tomography

1 INTRODUCTION

A single Non-Destructive Testing (NDT) campaign can be considered as a single data point on a Structural Health Monitoring (SHM) time-scale. Repeated NDT inspections can therefore contribute to a SHM system. Advances in NDT-methods are thus relevant for SHM.

GPR (Ground Penetrating Radar) is a powerful tool for the non-destructive inspection of reinforced concrete (rc) structures. The conventional way of carrying out radar surveys consists of data acquisition along lines followed by data processing and interpretation with the aim of obtaining structural information. This approach is economic and adequate in many cases. Recently, advanced techniques such as 3-D data acquisition and processing, data fusion, inversion and the investigation of material properties have been suggested. These techniques require additional effort when compared to conventional GPR and therefore there is a trade-off between the quality of investigation results and economical considerations. In this paper, the benefits of advanced techniques are demonstrated and discussed in relation to conventional GPR to provide a basis for future decisions.

2 CONVENTIONAL GPR

2.1 Radar principles

Ground-Penetrating-Radar is an electromagnetic non-destructive investigation method. It is also known as Surface Penetrating Radar or Electromagnetic Reflection Method. Mostly it is used in reflection mode where a signal is emitted via an antenna into the structure under investigation. Reflected energy caused by changes in material properties is recorded (Figure 1) and analysed.

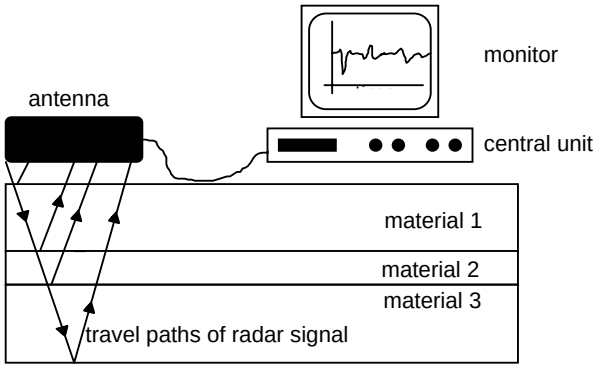

Figure 1: Radar principles

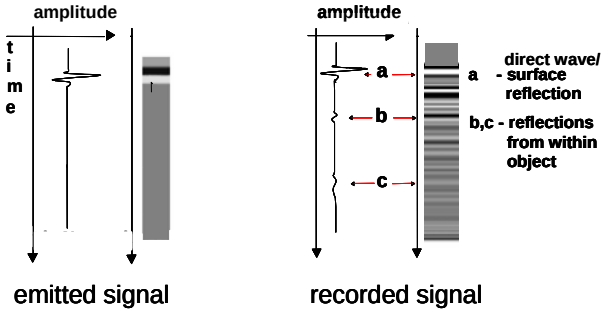

Figure 2: Emitted and recorded signal

A sketch of the emitted and recorded signal in wiggle and grey scale mode is presented in Figure 2. The signal recorded is usually referred to as a scan or a trace. The vertical axis is a time axis, its length in non-destructive-testing of concrete is typically less than 30 nanoseconds (ns). In order to obtain depths, the signal velocities in the different materials under investigation have to be known. There are several different ways to obtain these velocities, for example by the comparison of radar data with borehole information (Hugenschmidt and Mastrangelo, 2006).

Radar data can be displayed in different ways. In the examples shown below data are displayed in grey scale mode. Radargrams consist of a large number of traces lined up according to their acquisition position as sketched in Figure 3 where the antenna is moved in the X-direction recording data continuously. The radargram presented in Figure 4 represents a dataset acquired on the face of a retaining wall using a GSSI model 5100 antenna. The horizontal axis corresponds to the length in the X-direction and the vertical axis is a time axis. Several hyperbolae, three of them marked with arrows, are visible. These hyperbolae are caused by single rebars because the antenna is not only transmitting vertically into the wall but also sideways.

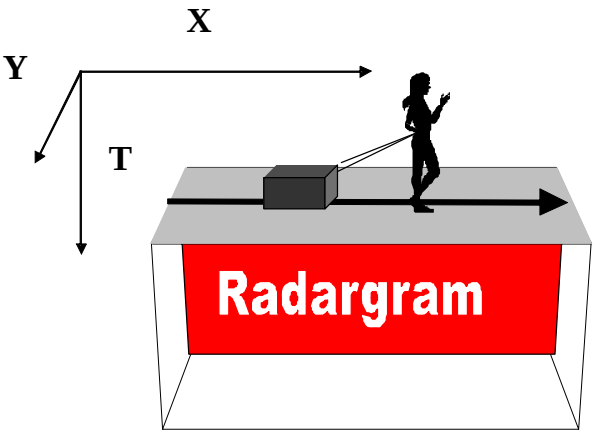

Figure 3: Schematic sketch of a radargram

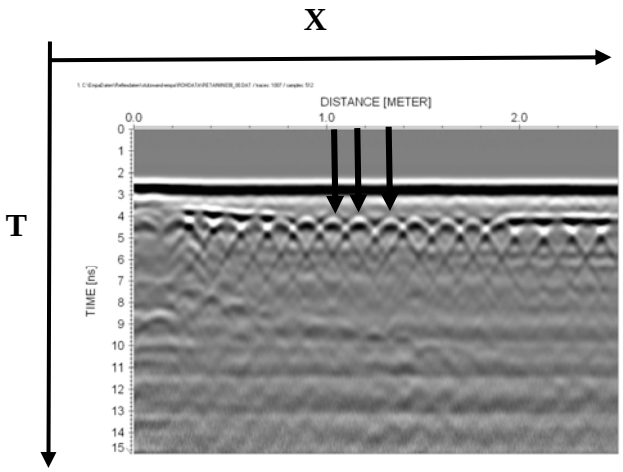

Figure 4: Example of a radargram from retaining wall, raw data

2.2 Data processing and interpretation

Data processing is applied to raw data for several reasons such as an improvement of the signal/noise ratio or the correction of the position of energy from dipping or point reflectors. An example for a processed dataset (the same dataset as in Figure 4) is presented in Figure 5. Besides an improved signal/noise ratio, the hyperbolae have been focused into dots during a process called migration resulting in a better representation of the reflecting single bars.

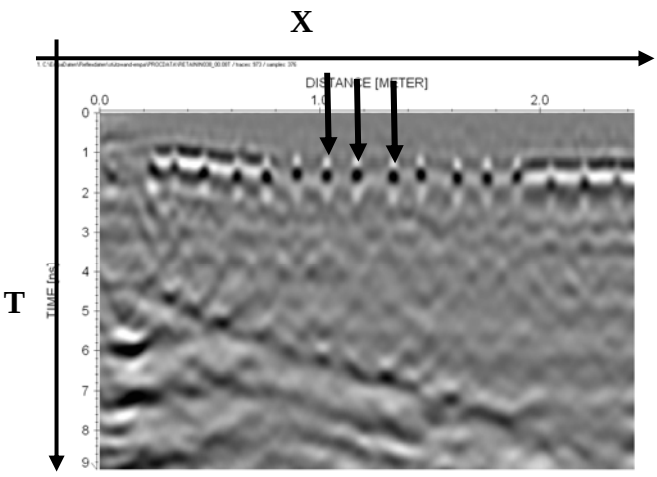

Figure 5: Example of a radargram from retaining wall, after 2-D processing

2.3 Limitations of conventional GPR

Conventional 2-D data acquisition and processing is fast and able to reveal many details of an inspected object. However, this approach has several implicit limitations. Radar antennas transmit and receive polarized waves, which means that there is directionality in the radar data. 2-D data can only be processed in two dimensions and thus the focusing during migration can

be applied only in the direction in which the radargram was recorded. The interpretation of radargrams depends highly on the experience of the interpreter and may therefore contain some cognitive bias. In addition, radar data do not only contain reflections but also auxiliary information such as the damping and phase of the signal that may not be exploited by an interpreter mainly searching for reflections. In order to utitilize the full potential of the radar method, several extensions to conventional GPR have been suggested and implemented in recent years.

3 ADVANCED TECHNIQUES

3.1 3D

When data are acquired not only along single lines but covering a whole area, for example by measuring along many parallel lines, slices at a constant time called time slices can be plotted (Figure 6). The time slice presented in Figure 7 was put together from 141 radargrams that had been processed with conventional 2-D processing as presented in Figure 5. Only signals recorded during a defined time-window are shown. Thus the two axis correspond to the dimensions of the surface on which data were acquired. When looking at Figure 7, it is obvious that horizontal bars pointing in the Y-direction show higher amplitude and sharper focus than vertical bars pointing in the X-direction. This is because of two reasons. First, data were acquired with an antenna whose polarization emphasizes horizontal bars. In addition, data were processed in 2-D focusing hyperbolae only in the X-direction.

The main advantage of 3-D surveys when compared to 2-D is that ambiguities during interpretation are reduced at the expense of an increased effort for data acquisition and processing.

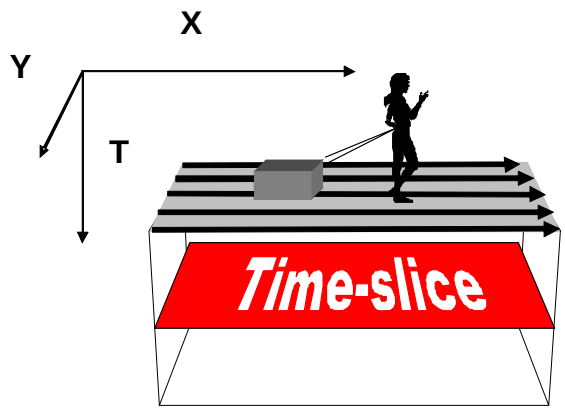

Figure 6: Schematic sketch of a time slice

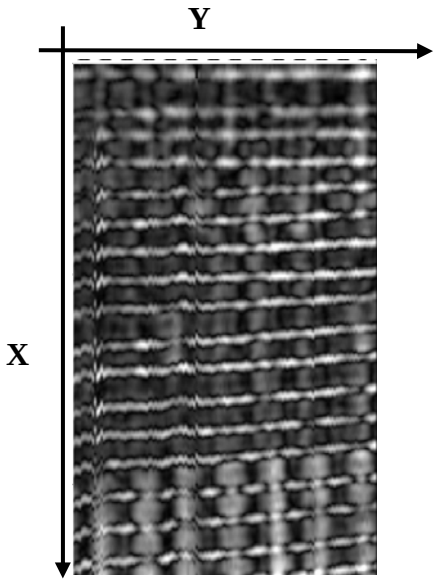

Figure 7: Example of time slice from retaining wall

3.2 3-D processing and data fusion

As identified in the previous chapter, 3-D data acquired with a single antenna followed by 2-D processing leads to results that have to be characterized as directional. In order to improve this shortcoming, data were acquired on the retaining wall with two antennas simultaneously. The antennas were orientated perpendicular to each other. This was followed by true 3-D processing and data fusion. Data fusion merged the datasets from the two antennas into one dataset using a wavelet algorithm (Hugenschmidt and Kalogeropoulos, 2008). In Figure 8 a time slice from the fused dataset is shown. When comparing this time slice to the one from Figure 7, it becomes clear that the mapping of the vertical rebars pointing in the X-direction has improved significantly. However, what is visible in Figure 8 is still reflected energy that has to be related to the physical properties of the object inspected.

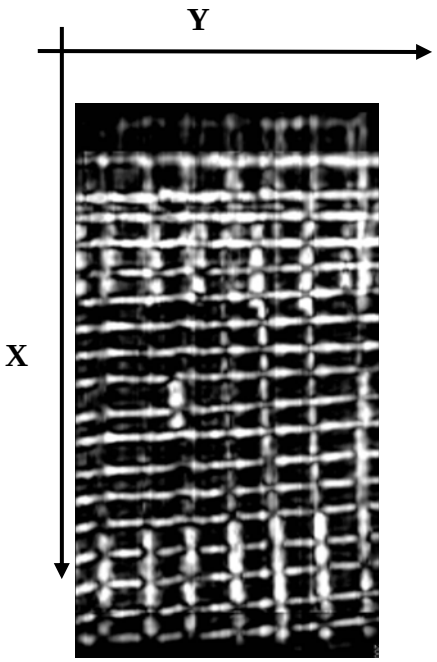

Figure 8: Example of time slice from retaining wall after 3-D processing and data fusion

3.3 Inversion

Inversion (Soldovieri et al., 2007, Ernst 2007) can be described as a process where a numerical model representing a physical environment is modified until it would produce a certain dataset. In other words, if a radar dataset has been acquired on a structure, a numerical starting model is built and synthetic radar data are generated using the starting model. The synthetic data are then compared to the real data and the model is adjusted. Then synthetic data are again generated using the updated model. This process is repeated until the synthetic data resemble the real data. The resemblance is measured via a predefined criterion such as a cost function.

A microwave tomography based inversion approach was applied to the two datasets acquired with the two perpendicular antennas followed by data fusion (Hugenschmidt et al., 2008). The final result is the three-dimensional modulus of the contrast function that accounts for the difference between the properties of the targets and those of the host medium (concrete hosting

rebar). The time slice from the retaining wall data after inversion and data fusion is presented in Figure 9. When comparing this result to the results presented in Figure 7 and Figure 8, it becomes clear that a complete map of both, horizontal and vertical rebars is provided and the reason for increased reflection amplitudes in some areas is elucidated (overlapping bars). In addition, the inversion results in a 3-D representation of the physical properties of the inspected object as opposed to reflected energy which is the output of the two approaches described above.

Inversion of radar data is still considered an advanced tool that is mainly used for research.

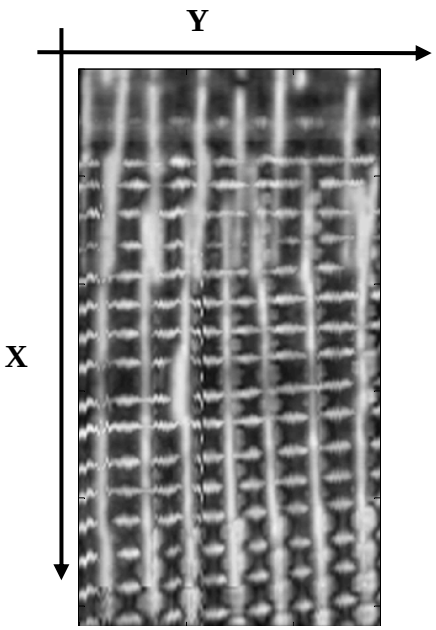

Figure 9: Time slice after inverse scattering and data fusion

3.4 Material properties

Until recently, GPR inspections were almost exclusively used for obtaining structural information such as layer thicknesses or positions of fixtures, such as tendon ducts. However, radar signals are not only reflected within structures but also affected by other influences such as the damping caused by an increased electrical conductivity of the material.

Corrosion of rebar in rc structures is a major problem in countries where salt is applied to roads for de-icing. The fact that most bridge decks are covered with asphalt and therefore inaccessible for direct inspection is an additional problem. On the other hand, the combination of chlorides and humidity can be expected to increase the electrical conductivity within concrete causing an increased damping of the radar signal.

In a laboratory experiment 9 specimens (Table 1) were produced (Hugenschmidt and Loser, 2008). Three different amounts of chloride were added to the mixture (0%, 0.4%, 1.0%) and the specimens were stored at three different relative humidities (35%, 70%, 90%). Radar data on all specimens were acquired 99 day after the casting of the probes using a pair of GSSI model 4205 horn antennas.

Results show a clear reduction of reflection amplitudes at the bottom of the specimens and an increase of reflection amplitudes at the concrete surface for increased contents of moisture and chlorides (Figure 10). The quotient (Figure 11) of the reflection amplitudes at the concrete surface and the bottom of the 90%-rel.humidity/1%-chlorides specimen is more than twice the quotient of the 35%-rel.humidity./0%-chlorides specimen. Therefore, the quotient approach is likely to provide stable results on real bridges, where additional factors may influence the results.

Table 1: Nine different specimens

relative humidity / chloride addition	35%	70%	90%
0.0%	Specimen 1	Specimen 2	Specimen 3
0.4%	Specimen 4	Specimen 5	Specimen 6
1.0%	Specimen 7	Specimen 8	Specimen 9

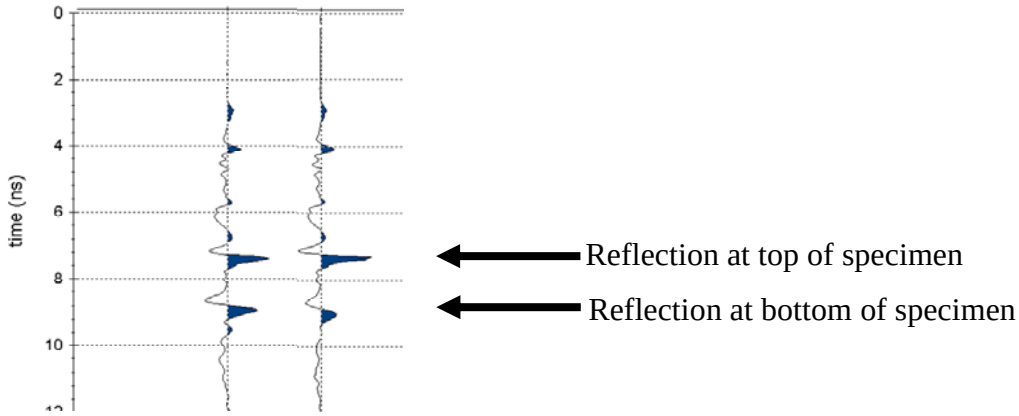

Figure 10: Radar signal from specimen without added chlorides stored at 35% r.h. (left) and from specimen with 1% added chlorides stored at 90% r.h. (right)

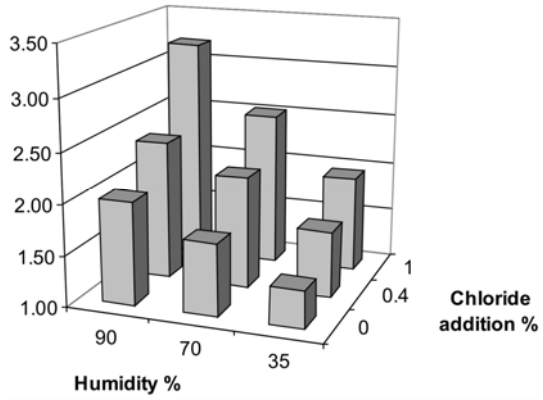

Figure 11: Quotient of reflection amplitudes

4 CONCLUSIONS

The combination of 2-D data acquisition, processing and interpretation is in many cases an economic and adequate approach for the non-destructive inspection of rc structures.

3-D data surveys can facilitate the interpretation of radar data considerably.

Data fusion merging datasets from different antenna orientations can eliminate the directionality of radar datasets.

Inversion results in a representation of the physical properties of the inspected object as opposed to reflected energy characterizing radar datasets. When applied to 3-D data recorded with different antenna orientations, this can result in a high quality map of both, horizontal and vertical rebars.

The investigation of chloride content and humidity has been shown to be feasible in laboratory experiment.

Advanced techniques cause more effort than conventional GPR. However, in many cases conventional GPR will neither eliminate all ambiguities nor exploit the whole potential of the radar method.

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