The inspection of retaining walls using GPR

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ABSTRACT

In hilly regions, retaining walls along roads, motorways and railway lines are numerous. In some cases the knowledge of the details of the construction is limited. If rehabilitation work becomes necessary, a detailed knowledge of the construction is desirable for the improved planning of maintenance and repair. This paper describes the application of Ground Penetrating Radar (GPR) for the inspection of retaining walls. The work was carried out in two steps. First, an investigation was carried out on large retaining walls at a Swiss motorway within the framework of a service contract. This included the development of an apparatus enabling high precision positioning of the antennas on the walls. Second, a pilot study was performed on a smaller wall with optimized acquisition and processing parameters. This included the use of antennas with different orientations and the fusion of the two corresponding datasets as well as true 3-D data processing. This paper describes the approaches to data acquisition and processing in the form of the two case studies. Results from different acquisition and processing strategies are compared and the benefits and limits are discussed.

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1. Introduction

The Swiss A9 motorway was built in the early seventies of the last century. It runs along the northern shore of Lake Geneva where there is a steep slope from the mountains towards the lake. As a result there is a large number of retaining walls particularly on the uphill side of the motorway. After more than 30 years in service, many of those walls are in need of repair and/or inspection. In order to evaluate the benefit of GPR as an inspection tool for those walls, a pilot study was carried out on one of the walls within the framework of a service contract. After the completion of this project, a second project was carried out on a smaller wall for the purpose of testing the benefits of enhanced data acquisition and processing.

GPR inspections of various concrete structures such as bridges, bridge decks and tunnel walls have been reported frequently (Taffe et al., 2003; Daniels, 2004; Hugenschmidt and Mastrangelo 2006; DGZIP, 2008) and can, in many cases, be considered routine applications of the radar method. The inspection of retaining walls poses challenges such as the controlled positioning of the antenna(s) on the wall face or the trade-off between the time required for data acquisition and data density. Limited literature is available on this subject.

2. Case study 1

A photograph of the wall and the westbound lanes of the motorway is presented in Fig. 1. The wall consists of 4 different levels, the heights of the different levels are varying between 6.5 m and 4.0 m. In the following text, the levels of the wall will be numbered from bottom to top with level 1 being the bottom level and 4 the top level.

In Fig. 2 the coordinate system used throughout this paper is shown. All data presented will be named as “A”-slices with A being the axis perpendicular to the slice.

2.1. Data acquisition

Data acquisition was carried out with a GSSI SIR-20 system in spring 2006. As this was a pilot study, three different antennas were tested. As one of the aims of this study was a test of the capability to locate the heads of rock anchors, a high accuracy of the antenna position was required. In order to achieve this, a semi-automated survey apparatus was developed. It consists of a rail system sitting on the copings of the different levels of the wall, an antenna box, a ladder-like guiding system for the antenna box, an electric motor for moving the box up and down the face of the wall, a survey wheel for controlling the vertical position of the box and triggering the data acquisition and an electronic protractor for monitoring the angle between the guiding system and the vertical line thus controlling the lateral position of the antenna. In Fig. 3 the top of the apparatus is shown together with the antenna box in the guiding system on the face of the wall.
Data were acquired along vertical lines corresponding to the X-direction in Fig. 2 on the face of the retaining wall. All antennas were orientated such that the E-field was pointing in the Y-direction. Line spacing was varied between 0.04 m and 0.1 m and the in-line sampling rate was 0.005 m. Apart from a gain function applied to ensure the optimal use of the dynamic range of the radar system, no data processing was performed during acquisition. The equipment used for data acquisition and the acquisition parameters are listed below.

Radar unit: GSSI SIR-20
400 MHz antenna: GSSI model 5103
900 MHz antenna: GSSI model 3101-D
1500 MHz antenna: GSSI model 5100
Apparatus for data acquisition: Empa custom-built

*antenna frequencies as provided by manufacturer.

** Acquisition parameters: **

| Samples per scan: | 512 (400 MHz model 5103 and 900 MHz model 3101-D antennas) 1024 (1500 MHz model 5100 antenna) |
| Line spacing: | 0.04 m (1500 MHz model 5100 antenna) |
| In-line sample rate: | 0.005 m |
| Scan-length: | 40 ns (400 MHz model 5103 antenna) 25 ns (900 MHz model 3101-D antenna) 20 ns (1500 MHz model 5100 antenna) |

After the equipment had been set-up, up to 30 vertical lines were acquired per hour. Depending on the line spacing this corresponds to a horizontal distance between 1.2 m and 3.0 m per hour.

2.2. Data processing

Data were copied to a personal computer and processed using REFLEXW software (Sandmeier, 2007). The 2-D processing sequence for the model 5100 antenna can be summarized as follows:

1. Bandpass filtering (lower cutoff 200 MHz, lower plateau 400 MHz, upper plateau 2700 MHz, upper cutoff 2900 MHz).
2. Static correction of picked direct wave.
3. Kirchhoff migration using \( v = 0.11 \) m/ns.
4. Gain correction using a linear gain function (0 dB at 0 ns and 20 dB at 20 ns).
5. Time cut to the same number of samples per scan for each dataset (corresponding to 12 ns for the 1500 MHz model 5100 antenna).
6. Resampling to 0.04 ns to reduce the size of the datasets.
7. Background Removal by subtraction of a mean trace (2-D data were transferred into 3-D datasets with and without Background Removal).

No corrections concerning the position of lines or traces were applied. This was unnecessary due to the high accuracy of the positioning made possible by the apparatus described in section 2.1. Following the 2-D processing sequence data were merged into 3-D files. All interpretation was based on 3-D files.

2.3. Interpretation and results

2.3.1. Antennas

In general, it can be assumed that high frequency antennas provide better resolution but less depth of penetration than low frequency antennas. As far as the resolution is concerned, this assumption can be easily confirmed by a comparison of the datasets obtained with the three antennas on level 2 of the retaining wall in Fig. 4-a the time...
range between 0 ns and 4 ns of a Y-slice is shown for the 1500 MHz antenna. Three single bars can be clearly distinguished. In Fig. 4-b the corresponding section acquired with the 900 MHz antenna is shown and Fig. 4-c presents the 400 MHz data. Obviously, the assumption of higher frequency corresponding to higher resolution is valid for this case. Looking at data from the same location but from a time window between 4 ns and 8 ns (Fig. 5), it becomes clear that the second assumption is not true in this case as the 400 MHz data do not offer any benefit when compared to the 1500 MHz section. This is probably due to the abundance of rebar present in the wall. As this was the case in most other locations as well, it was decided to restrict the interpretation to the 1500 MHz and 900 MHz data.

Fig. 3. Semi-automated survey apparatus; a) Top of apparatus and radar system; b) Guiding system with antenna box.

Fig. 4. Y-slices, 0–4 ns; a) 1500 MHz antenna (top); b) 900 MHz antenna (middle); c) 400 MHz antenna (bottom).

Fig. 5. Y-slices, 4–8 ns; a) 1500 MHz antenna (top); b) 900 MHz antenna (middle); c) 400 MHz antenna (bottom).
2.3.2. Rebar

In Fig. 6-a a T(ime)-slice ($t=0.92$ ns) from level 2 is presented. In the lower left and upper central region the first layer of rebar is visible, whereas in all other regions the rebar is at greater depth. The alternative explanation of varying signal velocities within the concrete due to changes in material properties seems rather unlikely, because the original concrete and the exposure to environmental conditions are probably similar for the same section of a single wall. Two strong reflections from structures present in addition to the rebar are marked with arrows.

In the corresponding slice at $t=1.6$ ns (Fig. 6-b) the top layer of rebar is mapped almost completely. Vertical bars (bars parallel to the X-axis) cause weaker reflections when compared to horizontal bars because of the antenna orientation during data acquisition and because of the application of a background removal during data processing. Also, in this figure the accuracy of the acquisition apparatus becomes apparent, as only minor deviations of a maximum of about 0.02 m are visible (white arrow). These are mainly caused by the roughness of the surface of the wall. At $t=5.16$ ns (Fig. 6-c) a second layer of rebar is visible, however it is obvious that signal quality as well as resolution have deteriorated considerably.

2.3.3. Joints and dowels

Two Y-slices from level 3 are presented in Fig. 7. The line in the upper Fig. 7(a) was acquired at a distance of 4.3 m from a joint separating two different sections of the wall. Two layers of rebar are visible. The line presented in the lower Fig. 7(b) was acquired on the joint. Only one layer of rebar is present but there are three additional reflections (arrows). As it is common practice to join separate sections of concrete with dowels and, as such, these three reflections were interpreted as dowels.

2.3.4. Rock anchors and anchor heads

As there was no additional information such as expected depth, size or approximate position of the anchor heads available, it was not possible to decide conclusively whether a reflection present in the radar data was caused by an anchor head or not. Possible locations of anchor heads were therefore defined in two steps:

- The 3-D datasets were searched for reflections that could not be related to rebar, dowels or other structures expected to be present in the walls.
- The position of these reflections was compared to structures visible on the face of the walls such as water outlets. Anomalous reflections without corresponding structures visible on the wall faces were then considered as possible positions for the anchor heads.

In the upper Fig. 8 a Y-slice from level 1 is presented. A prominent reflector is marked with a white arrow. In the lower Fig. 8 the Y-slice is combined with a T-slice giving an indication of the X–Y extension of the reflector.

Fig. 9 shows a map of possible anchor head positions (black rectangles) for level 1. It is likely that some of those positions are the result of other reflectors than anchor heads. However, based on radar data alone a distinction between anchor heads and other reflectors is not possible.

3. Case study 2

In case study 1, it was shown that the inspection of large retaining walls with GPR can provide detailed results on structural elements. Room for improvement was spotted mainly with respect to the directionality of the results (e.g. the ability to image horizontal versus vertical rebar). It was therefore decided to carry out a second study.
with the focus on strategies for the reduction of the polarization dependence of radar results using two perpendicular antennas, as shown in Fig. 10.

3.1. Data acquisition

Case study 2 was carried out on a smaller wall (Fig. 11). The same apparatus as in case study 1 was used for data acquisition. Two 1500 MHz antennas were placed perpendicular to one another in the antenna box and the data from both antennas were recorded simultaneously. The inspected part of the wall was 1.41 m long and about 2.50 m (±0.02 m) high. The acquisition parameters can be summarized as follows:

- Scans per meter: 400 for each antenna
- Samples per scan: 512
- Line spacing: 0.01 m
- Trace length: 15 ns
- Distance between antenna centres: 0.197 m

After the system had been set up, an average of 40 lines was acquired per hour.

3.2. Data processing

Data processing was carried out in three steps. Firstly, data were processed line wise (Y-slices, 2-D processing), then data were combined into two 3-D datasets (one for each antenna) for 3-D migration and finally the two datasets were merged by adding corresponding samples together using Matlab (The Mathworks Inc., version 7.4).

The 2-D processing was applied line by line to the datasets of both antennas. The processing sequence can be summarized as follows:

- Time shift
- Dewow (mean subtraction) filter
- Gain correction, using a linear gain function (0 dB at 0 ns and 20 dB at 15 ns)
- Background removal by subtraction of a mean trace
- Spiking-deconvolution: This processing was applied mainly to increase resolution. The filter was calculated using a recursive autocorrelation algorithm (Levinson) on part of the traces (0 ns–13 ns). This filter was then convolved with the original traces with 50% white noise added.
- F-K filter: The box coordinates of the F-K filter were (0 kHz, 70 MHz; –20 kHz, 1000 MHz; 20 kHz, 1000 MHz; 0 kHz, 2700 MHz). The role of this filter was to reduce the effect of white noise added during the deconvolution.

Following 2-D processing, lines were merged into 3-D datasets. This was done for both antennas separately. The data were migrated in 3-D using Stolt’s algorithm and a signal velocity of 0.105 m/ns. The Stolt algorithm was used for the 3-D migration because it is faster than the Kirchhoff algorithm (used for case study 1) and therefore well suited for large 3D datasets (Sandmeier K. J., personal communication). Two lines (Y-slices) from the two datasets after processing are presented in Fig. 12. Obviously the horizontal E-field antenna provides a better result for the horizontal rebars and the vertical E-field antenna is more sensitive to vertical rebars. The 2-D processing and the 3-D migration were carried out using REFLEXW software (Sandmeier, 2007).

3.2.1. Data fusion

Data fusion was the final step of data processing merging the data from both antennas. As this was done line by line, the 3-D datasets were split into the original number of 141 lines per antenna. All computations were carried out using Matlab software (The Mathworks Inc., version 7.4). As the antenna centres were 0.197 m apart during data acquisition and because the time window of the recordings was slightly different, a geometric correction was applied to generate Y-
slices with the same number of samples in the X- and T-directions. This was done by adding samples with a value of zero (Fig. 12).

In Fig. 13, two sections of traces from the two antennas recorded in the same position are shown. These traces will serve as examples for the data fusion.

Based on the work by Kohl et al. (2003), two data fusion algorithms were tested. The first computes the average of amplitudes:

\[ A_s, t = \frac{1}{2} \sum_{i=1}^{2} A_{s,i,t} \tag{1} \]

where \( A_{s,t} \) is the amplitude from sample \( s \) in trace \( t \), and \( i \) denotes datasets 1 and 2. The application of this algorithm to the two traces shown in Fig. 13 produces the result presented in Fig. 14. This approach adds only little noise but leads, in many locations, to a reduction of peak amplitudes.

The second approach uses the maxima of the amplitudes:

\[ A_s, t = \max \sum_{i=1}^{2} A_{s,i,t} \tag{2} \]

Using this approach leads to the result presented in Fig. 15. Here the peak amplitudes are well preserved but at the expense of an increased noise level.

The disadvantage of the two approaches described above is that they do not take into account the fact that both signals are not exactly in phase. This can change the amplitude of a reflected signal and the size or the position of an interpreted reflector.

Here, it is proposed to use a different approach, each trace is decomposed into sub-spaces using finite time, oscillating, zero mean signals called wavelets (Mallat, 1989). Then the corresponding sub-spaces from both traces are merged and reconstructed into a fused trace. The decomposition conducted with predefined wavelets

\[ \text{Horizontal E-field} \quad \text{Samples (discrete time)} \quad \text{Vertical E-field} \]

\[ \text{Vertical rebar} \quad \text{Horizontal rebar} \]

\[ \text{Geometric correction in } x \]

\[ \text{Traces} \quad \text{Traces} \]

\[ \text{Vertical rebar} \quad \text{Horizontal rebar} \]

\[ \text{Geometric correction in } x \]

\[ 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \quad 450 \quad 500 \]

\[ 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \quad 450 \quad 500 \]

Fig. 11. Test site 2 with apparatus for data acquisition.

Fig. 12. Y-slices; horizontal E-field (left); vertical E-field (right); 100 discrete time samples correspond to 2.93 ns, 401 traces correspond to 1.0 m.
containing frequency and time information is called continuous wavelet transform.

3.2.1.1. Continuous wavelet transform. According to continuous wavelet transform theory a function \( f(t) \) can be decomposed into a set of basic functions \( \psi_s, \tau (t) \) (Eq. (3)), were the variables \( s \) and \( \tau \) denote scale and translation respectively and \( \star \) denotes the complex conjugate.

\[
\gamma(s, \tau) = \int f(t) \psi_s^\star (t) dt.
\]

The inverse wavelet transform is given by:

\[
f(t) = \int \int \gamma(s, \tau) \psi_s, \tau (t) d\tau ds.
\]

The child or scaled wavelets are generated from a single basic wavelet \( \psi(t) \), mother wavelet:

\[
\psi_s, \tau (t) = \frac{1}{\sqrt{s}} \psi \left( \frac{t - \tau}{s} \right).
\]

In Eq. (5), \( s \) is the scale factor, \( \tau \) is the translation factor and \( s^{-1/2} \) is the energy normalization across different scales.

As previously mentioned the wavelet used is predefined. Numerous wavelets types are mentioned in the literature. After testing several families of wavelets (Daubechies, Symlets, Coiflets, Haar) during this study it was concluded that Coiflet wavelets (Fig. 16) gave the best result. This is because, according to the literature, the shape of the mother wavelet should be as close as possible to the shape of the emitted radar pulse (Perrin et al., 2000).

3.2.1.2. Discrete wavelet decomposition and Fast Wavelet Transform. For computational reasons, the continuous wavelet Eq. (5) has to be changed into a discrete form, where \( j \) and \( K \) are integers and \( s_0 > 1 \).

\[
\psi_{j,k}(t) = \frac{1}{\sqrt{s_0}} \psi \left( \frac{t - k\tau_0}{s_0} \right).
\]

In this study the decomposition was carried out with an algorithm designed by Mallat (Mallat, 1989) using Matlab software (The Mathworks Inc., version 7.4), the Fast Wavelet Transform, which can be summarized as passing the traces through a series of filters to decompose each sub-space into two smaller sub-spaces. For that the lower frequency part of the signal (low pass, Eq. (7)) and the upper frequency part of the signal (high pass, Eq. (8)) are analyzed.
frequency part of the signal (high pass, Eq. (8)) are calculated at each
decomposition level, giving approximation coefficients and details
coefficients respectively (Fig. 17).

\[ y_{\text{low}}[n] = (x^*g)[n] \]  
\[ y_{\text{high}}[n] = (x^*h)[n]. \]  

(7)  
(8)

where \( y_{\text{low}} \) and \( y_{\text{high}} \) are the two resulting sub-spaces of the previous
x signal, g can be considered as the wavelet low pass filter, h as the
high pass filter and \( n \) is the sample number (discrete time). For
computational reasons, the filter outputs are downsampled by a factor
of 2 (Fig. 17).

This operation is recursive and can be executed with a number of
predefined levels. In this study, five levels were used after different
numbers of levels have been tested. Fig. 18 shows this decomposition
for three levels.

With both signals decomposed into the desired levels, the fusion
operation can be applied. To do so it is required to define the fusion
rules. In this study it has been observed that averaging the
approximation coefficients and taking the maximum of the detail
coefficients gave the best result. After the coefficients of each level
have been fused, Eq. (4) is used to recompose the merged traces.

The result of the wavelet fusion is presented in Fig. 19. The wavelet
fusion algorithm combines the advantages of the average and
maximum methods by keeping noise low and maintaining peak
amplitudes. Fig. 20 shows sections of Y-slices of the two datasets
(a and b) together with the results of the different fusion
methodologies (c, d and e).

This comparison confirms the conclusions from the comparison of
single traces. The mean algorithm leads to a reduction of amplitudes,
particularly visible between traces 200 and 300. The maximum
algorithm leads to a high amplitude, high noise result. The wavelet
fusion algorithm combines the advantages of the mean and maximum
approaches, mapping both, vertical (traces 100–200) and horizontal
(traces 200–300) rebar, appropriately. Obviously, the results of the
mean and wavelet algorithm show some similarity. However, when
focusing on the horizontal rebar (traces 200–300), the wavelet result
is clearly advantageous.

Fig. 21 presents a T-slice from the dataset fused with the wavelet
approach ranging from 1.45 ns to 2.08 ns produced with OsiriX
software (www.osirix-viewer.com). The fused dataset maps hori-
zontal and vertical structures and therefore combines the informa-
tion from the two antenna orientations. The combination of
information from different sources into a single dataset facilitates
the interpretation of the data and enhances the accessibility for
non-specialists.

4. Conclusions

The apparatus developed for the inspection of retaining walls
enables an efficient data acquisition on large and small retaining
walls with a high accuracy of positioning. Depending on the height
of the wall, between 30 and 40 vertical lines were acquired per
hour.

In case study 1, the 400 MHz antenna did not improve the depth
of penetration when compared to the 900 MHz and 1500 MHz
antennas. This is probably due to the abundance of rebar within the
wall.

With the 900 MHz and 1500 MHz antennas it was possible to map
accurately several layers of rebar and additional structures such as
dowels in case study 1.

Although, in case study 1, several anomalous reflectors were found
on each level of the wall, it is not possible to decide whether those are
related to rock anchors or not, based on radar data alone.

The fusion of datasets acquired with antennas with different
orientations can significantly reduce the directionality of radar data.
Thus, longitudinal objects with different orientations can be mapped
properly. The wavelet fusion algorithm provided better results than
the maximum or average algorithms when applied to the top layer of
rebar. The combination of information from different sources into a
single dataset facilitates the interpretation of the data and enhances
the accessibility for non-specialists.

Future work will focus on advanced processing and inver-
sion schemes applied to deeper structures and the back wall
reflection.

![Fig. 17. Generation of two downsampled subspaces (Mallat, 1989).](image1)

![Fig. 18. Fast Wavelet Transform decomposition tree, three levels (Mallat, 1989).](image2)

![Fig. 19. Traces merged with wavelet fusion algorithm and original traces; 1500 MHz antennas, 100 samples correspond to 2.35 ns.](image3)

![Fig. 20.](image4)
Fig. 20. a) and b) Sections of original Y-slices; c)–e) Sections of fused Y-slices; 100 discrete time samples correspond to 2.93 ns, 401 traces correspond to 1.0 m, 1500 MHz antennas.

Fig. 21. T-slice, dataset fused with wavelet algorithm, $t = 1.45$–2.08 ns corresponding to approximately 0.075 m to 0.11 m, 1500 MHz antennas.
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