A noise reduction method for Ground Penetrating Radar signal based on wavelet transform and application in tunnel lining

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Abstract. One of the major limitations that hinder the use of ground penetrating radar (GPR) in civil engineering is the inevitable noise interference associated with the GPR signal. This study proposes a noise reduction technology for a GPR signal by utilizing the excellent time-frequency localization properties of a wavelet and by analysing the characteristics of the wavelet function and the principles of wavelet noise reduction. A Daubechies wavelet is selected as the wavelet function, and the wavelet decomposition and re-construction is performed on a single channel radar signal. The images of tunnel lining from GPR are compared before and after wavelet transform, and the wavelet transform processing is proved to be capable of separating noise as well as of improving the signal-to-noise ratio. The results show that wavelet transform processing is found useful to improve the recognition of image and the accuracy of radar signal interpretation.

1. Introduction

Ground penetrating radar (GPR) is widely used in the quality inspection of tunnel lining. However, due to very complex rock media, radar gets inevitably disturbed by noise and gets cluttered. In early studies, because of the similarities in the propagation form and reflection profiling data of the electromagnetic waves and seismic waves, seismic data processing method was also used to process the data of GPR (Chen and Xiao, 2005)[1]. A thought of applying a wavelet transform in signal de-noising was proposed in 1989 (Larsoneur, 1989; Morlet, 1989) [2]. Based on MRA, a multi-resolution wavelet network was constructed using a compactly supported orthogonal wavelet, where wavelet function and scaling function are applied in wavelet network, and by taking advantages of their complementary properties, the multi-resolution wavelet network was found to have a clear global and local error estimate, lower computational complexity and excellent adaptability (Bahavik, et al. 1993) [3].

The use of an atomic decomposition-based tracking de-noising method was also studied(Chen and Donoho, 1999) [4]. A discrete wavelet transform with an artificial neural network were coupled to propose a method for monitoring the water table (Adamowski and Chan, 2011) [5]. In use of the adaptive threshold method, Joewono studied the use of compression wavelet analysis in retinal recognition technology with low SNR (Joewono, 2015) [6]. The research laid the foundation for the wavelet theory and these wavelet functions and methods have been widely applied and proven in seismic de-noising, image processing and other broad areas. These studies provide a guideline for the

use of the wavelet theory in de-noising GPR signal obtained during inspecting a tunnel lining structure.

2. The wavelet transform theory and apply on GPR signal processing

2.1. Wavelet transform

The wavelet transform methods include "threshold de-noising" approach (Donoho, 1995) [7]. It accounts that the wavelet coefficients corresponding to the signal contain important information of signal, and are of a small number with large amplitude. The wavelet coefficients corresponding to the noise are uniformly distributed, and are of a large number with small amplitude.

2.2. Wavelet transform de-noising threshold method

The wavelet transform threshold method can be divided into two types, namely, soft threshold and hard threshold (Donoho and Johnstone, 1994; Donoho, 1995) [8]. Hard threshold method is to set a value of 0 for the wavelet coefficients that are smaller than the set threshold value. The values of the wavelet coefficients that are greater than the threshold value are retained without any treatment. On the other hand, while the soft threshold method also sets a value of 0 for the wavelet coefficients that are smaller than the set threshold value, the values of the wavelet coefficients that are greater than the threshold value are set to the new shrunken values obtained by subtracting the threshold value from their original values.

The formula for the hard threshold is given as:

$$\lambda_{hard} = \begin{cases} \chi(t) & |\chi(t)| > \lambda \\ 0 & |\chi(t)| \leq \lambda \end{cases} \tag{1}$$

And the formula for the soft threshold is given as:

$$\lambda_{soft} = \begin{cases} (|\chi(t)| - \lambda)\operatorname{sgn}(\chi(t)) & |\chi(t)| > \lambda \\ 0 & |\chi(t)| \leq \lambda \end{cases} \tag{2}$$

Where $\chi(t)$ is signal wavelet transfer function; λ is selected threshold; sgn represents the sign function, it means that the soft threshold method set the wavelet coefficients , the absolute value of which does not exceed threshold to zero, the other factor reduction processing in accordance with thresholds.

As seen from the above formula (5) (6), since the hard threshold function is a non-continuous function, when high-frequency coefficients are quantized, the coefficients are highly sensitive to the small changes around the threshold value. This leads to a numerical situation which is prone to mutation. Thus, after a hard threshold, the output image is not very smooth, and the image may sometimes consist of ringing, pseudo-Gibbs effects, etc. Nevertheless, the hard threshold method can preserve the local features, such as edges, very well. On the other hand, the soft threshold method may cause blurred edges, but results in a relatively smooth output image.

2.3. Determination of wavelet decomposition level

The actual process of radar signals shows that the wavelet decomposition level is not necessarily better when it is larger. As measured on a single channel radar signal corresponding to the random distribution of white noise de-noising simulation, the original signal sampling points were 512. This paper extracted half the length of it, which means information of the first 256 points. The signal was processed by using a DB4 wavelet. The decomposition level was chosen as 6 and the information about scale change was given for each level. Listed below are the high (low) frequencies of the re-constructed image for decomposition levels 1-6. When s represents the noisy signal; a(i) represents the low-frequency coefficients re-constructed image at the i-scale decomposition; and d(i) represents the

high-frequency coefficients of the re-constructed image at the i-scale decomposition, s=a(6)+d(6) +d(5) +d(4) +d(3) +d(2) +d(1). Then, formula (4) was used to reconstruct the desired de-noising image. Figure4 shows that the re-constructed signal basically retains the mutated portion of the original signal; the distortion is small. Figure5 shows that when the scale is enlarged by four times, the effective signal retained little significance. Based on the numerical results, it was found that when the number of layers selected was three. The re-constructed signal resembles the closest to the original signal.
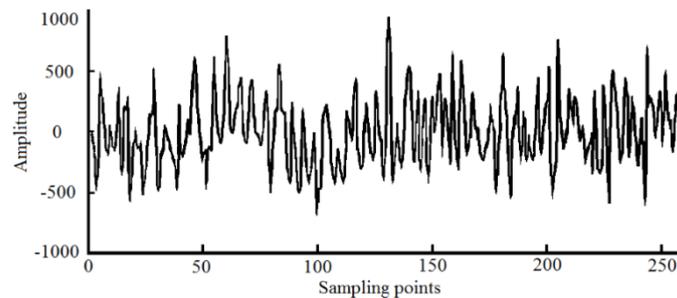
Figure 1. Analog random noise
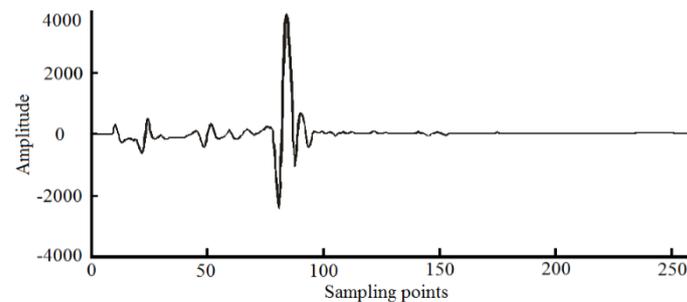
Figure 2. One trace GPR signal curve
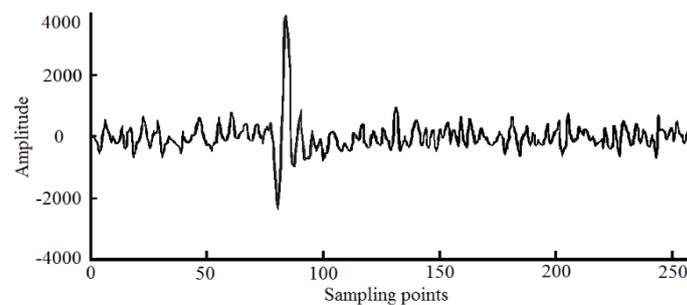
**Figure 3.** Synthesized signal after adding random noise
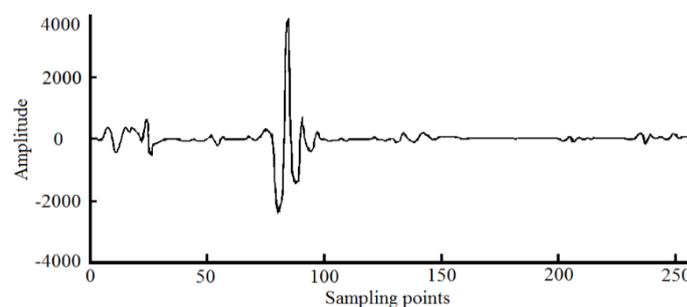
**Figure 4.** Re-constructed signal after de-noise
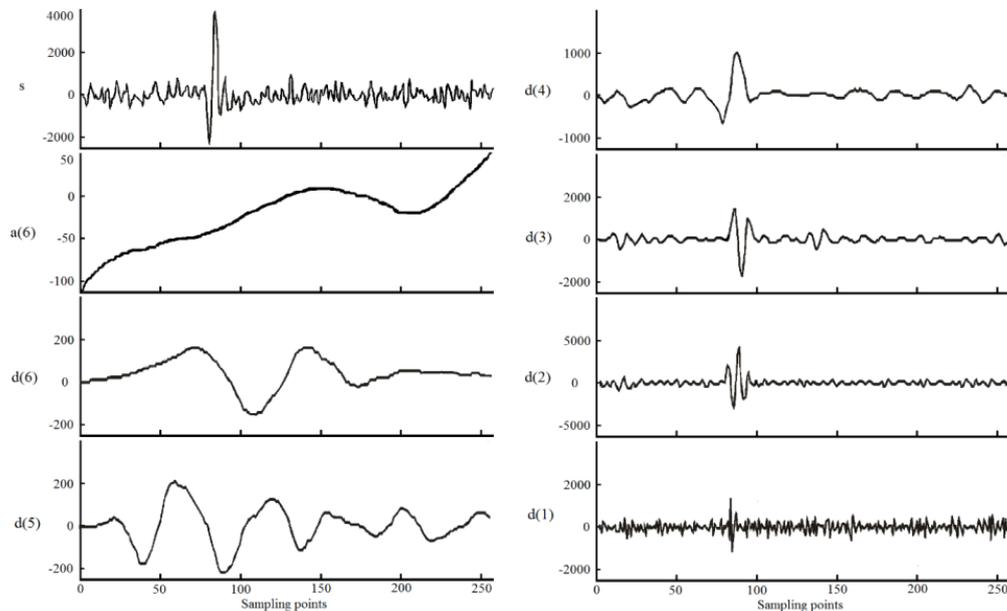
Figure 5. One trace signal by DB DWT at level 6

3. Engineering application

Yushan tunnel is located in Ji'an city, Jiangxi province, China. The mileage for the survey line at the beginning and the end are ZK190 + 640 and ZK190 + 672 which is located in four surrounding rock area with 0.2 m thick concrete lining with steel arch spaced at 1 m center to center.

Figure 6. Data collection during the field quality inspection of Yushan tunnel lining

Quality inspection of the tunnel lining was performed by using GPR equipment of SIR 3000 model produced by US GSSI. Antenna transmit center frequency was 400 MHz and emission rate was 100 KHz. Every signal comprised of 512 sampling points. The data was stored in 16 bit format. The dielectric constant was six. The equipment took continuous measurement for a measuring line along the tunnel vault having a length of 32 m.

A multi-DB4 wavelet decomposition was performed on the measured radar data profiles. The low frequency coefficients and high frequency coefficients re-constructed sections of the signals were obtained.
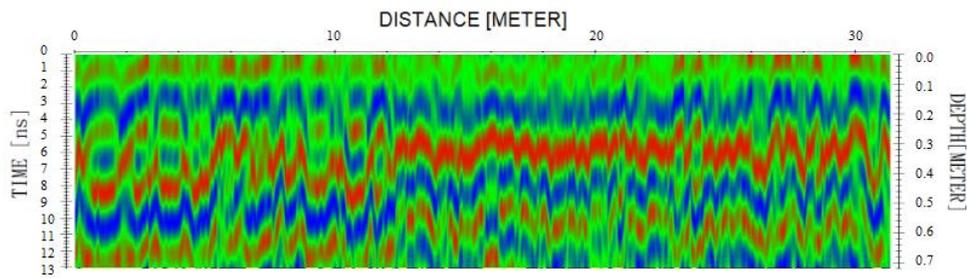
Figure 7. Original profile of GPR
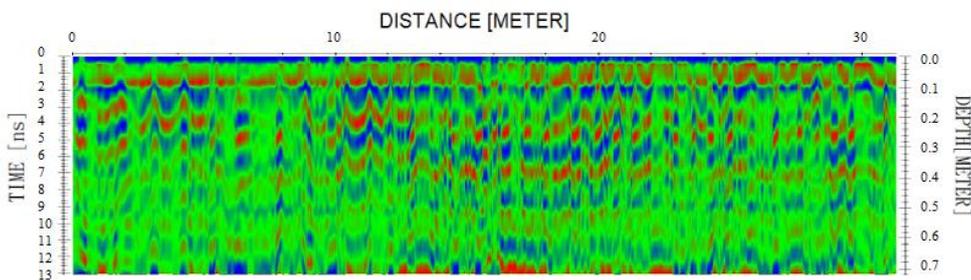
Figure 8. Re-constructed profile at level 1 by DB dwt
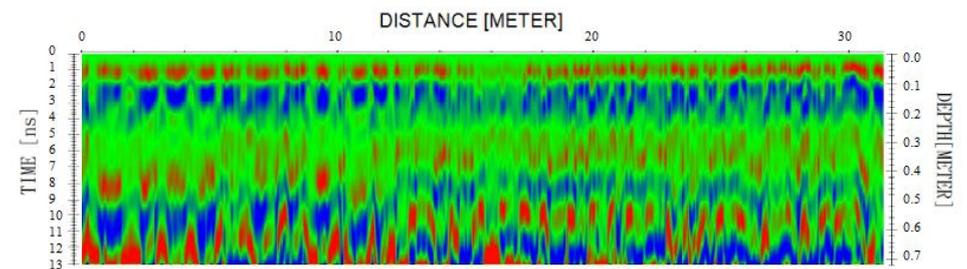

Figure 9. Re-constructed profile at level 2 by DB dwt

By comparing Figure 7 to 9, it is found that by multilayer wavelet decomposition, noise was focused on scale 3 profiles, the main signal of steel arch and lining interface remained in scale 1 profile. By combining the profile spectra for several scales, the scope of the band-pass filter is easy to determine and it is also easy to deal with traditional methods. Comparing figure 7 and figure 10, it can be seen that figure.10 more clearly reflect the steel arch and lining interface than figure 7. The number of steel arch is 35 and their intervals are 0.94 m. The lining thickness is 0.2 m and the bond between lining concrete and rock was good without empty area or honeycombing. Thus, the image resolution is higher after wavelet transform processing, and the interpretation can be more accurate.
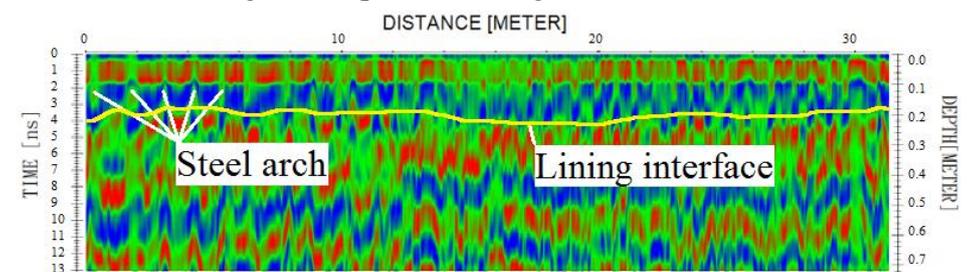

Figure 10. Profiles re-constructed by the inverse wavelet transform method

4. Conclusion

By using the differences of characteristics in the wavelet domain between the radar signal and the noise, a wavelet transform was applied in ground penetrating radar signal processing. The signal was decomposed into different frequency bands. Depending on the specific circumstances, by selecting a wavelet function and function parameters appropriately, the applied wavelet transform was effective to remove the noise, to implement signal noise separation, and to improve the resolution and the signal-to-noise ratio. Wavelet transform method was used in processing the GPR data obtained during the quality inspection of the lining of Yushan tunnel in China. The results showed that, in the image area, the lining thickness was 0.2 m, steel arch number was 35, lining interface was uniform, the bond between concrete and rock was good and there was no empty area or honeycombing. Compared with the original GPR image, the images processed by wavelet transform clearly reflect the distribution of each reflection surface and steel arch in internal lining. The comparison of the images confirmed that the wavelet transform method works well. The method improves the recognition of various features in the original image and increases the accuracy of the radar signal interpretation. Moreover, the method shows an excellent promise for GPR data processing in future.

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