Filtering of Seawall GPR Signal by means of Multi-Wavelet Transform

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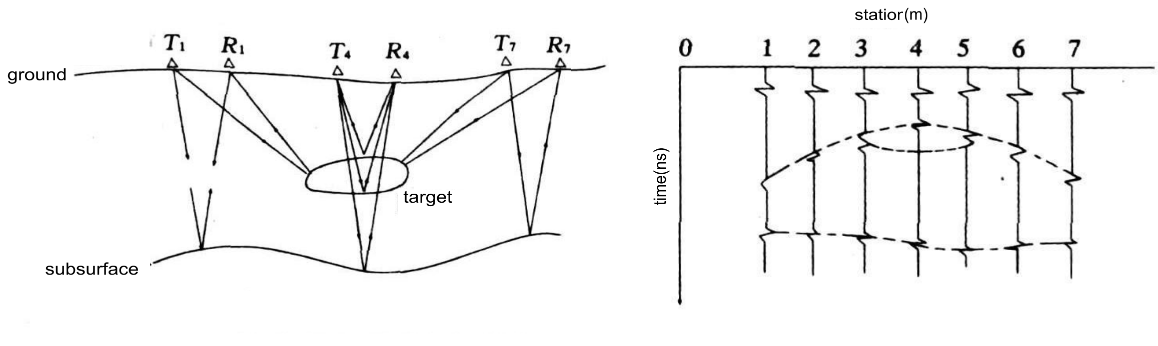
ABSTRACT
Background noise is and will always be an issue accompanying any type of ground-penetrating-radar (GPR) data acquisition and processing. Filtering is sometimes important for GPR data interpretation. In this paper, the principle and the characteristic of a multi-wavelet filter are presented briefly. And then the steps required to filter a GPR signal using a multi-wavelet filter are presented. The image changes of two theoretical models from the forward-calculated image to that of mixed with noise and that processed using a multi-wavelet-filter show that a multi-wavelet filter can be an effective tool for GPR signal filtering. As an example the field GPR signals of a seawall exhibiting water leakage were processed using a multi-wavelet transform. And the processed result is interpreted. The interpreted result facilitated the smooth completion of seawall waterproofing treatment.

General Terms
Ground-penetrating radar (GPR); wavelet transformation; noise reduction, signal processing

Keywords
Ground-penetrating radar (GPR); multi-wavelet transformation; filter; noise reduction, signal processing

1. INTRODUCTION
Ground-penetrating radar (GPR) is an electromagnetic (EM) tool used to evaluate the location and depth of buried objects in a dielectric medium, and to investigate the presence and continuity of natural subsurface conditions and features, via the reflection and scattering signals at the EM characteristics of discontinuities without the need for drilling or digging [1]. In brief, the function of GPR is to depict the geometric and physical characteristics of underground objects [2]. Its principle of operation is shown in Figure 1.



(a) (b)

Fig. 1 Operational principle of GPR

(a) schematic of surveying arrangement and (b) test result

GPR signals are very complicated, and include many kinds of disturbances. Real-time GPR recordings are mutable and not easily distinguished. Background noise is and will always be an issue accompanying any type of data acquisition and processing. The noise in a signal has a considerable negative effect on the result of interpretation. The ideal interpretation of a GPR image cannot be achieved if its signal-to-noise ratio is too low. So filtering and reduction of noise is sometimes critically important, and must be applied to GPR data before interpretation in order to ensure that the most useful information is extracted from the sampled data.

Nowadays, wavelet transformation has been widely used to process GPR signals. Because of its space and frequency double-locality character, a wavelet transform can be used not only to confirm the spatial position of singularity but also to suppress the noise of GPR signals [3-7]. A multi-wavelet transform exhibits orthogonality, symmetry, and compact support. In the work reported in this paper, a multi-wavelet transform was used to filter GPR data.

2. MULTI-WAVELET TRANSFORM
The wavelet is a breakthrough of theory and practice after the Fourier transform in the field of mathematics. It is a one time–frequency analysis method and has the characteristic of multi-resolution analysis, as well as the ability to characterize a signal's local features in both time and frequency fields [8]. It

analyzes the signal through one flexible time and frequency window. In addition, it is uniquely applicable to transient non-stationary signals and broadband signal analysis, and is most suitable for dictation and display of transient, abnormal signals mixed with normal signals.

The multi-wavelet is a relatively new development in wavelet theory. Compared with the former scalar wavelet, the multi-wavelet is formed by multiple-scale functions or vector-scale functions. It may exhibit many characteristics simultaneously, such as orthogonality, symmetry, short support, high-order vanishing moments [9–12], and so on.

The collection of r scaling functions $\varphi_0(t-k), \varphi_1(t-k), \ldots, \varphi_{r-1}(t-k)$ is called multi-scaling functions, and the collection of r wavelet functions $\psi_0(t-k), \psi_1(t-k), \ldots, \psi_{r-1}(t-k)$ is called multiple-wavelet functions, which forms the base of W_0 space:

$$\begin{cases} \Phi(t) = [\phi_1(t), \phi_2(t), \cdots, \phi_{r-1(t)}]^T \\ \Psi(t) = [\psi_1(t), \psi_2(t), \cdots, \psi_{r-1(t)}]^T \end{cases} \quad (1)$$

Here $\Phi(t)$ and $\Psi(t)$ are respectively the transform of the scaling function and the wavelet function, which, together, are called a multiple-wavelet, or multi-wavelet transform.

$\Phi(t)$ and $\Psi(t)$ consist of the following two scaling functions:

$$\begin{cases} \Phi(t) = \sqrt{2}\sum_k H_k \Phi(2t-k), \\ \Psi(t) = \sqrt{2}\sum_k G_K \Phi(2T-K), \qquad k \in Z \end{cases} \quad (2)$$

where H_k and G_k are $r \times r$ constant matrices.

Extending the decomposition and synthesis algorithm from a single-wavelet transform to a multi-wavelet transform, we can obtain

$$\begin{cases} C_k^{(i+1)} = \sum_n H_{(n-2k)} C_n^{(i)}, \\ D_k^{(i+1)} = \sum_n G_{(n-2k)} C_n^{(i)} \end{cases} \quad (3)$$

the reconstruction algorithm of which is as follow:

$$C_n^{(i)} = \sum_k H_{(n-2k)}^T C_k^{(i+1)} + \sum_k G_{(n-2k)}^T D^{(i+1)}_k. \quad (4)$$

3. STEPS OF GPR SIGNAL FILTERING VIA MULTI-WAVELET TRANSFORM

The essence of multiple-wavelet filtering is multi-resolution analysis using multi-wavelet. First, a signal is spread in scalar space, and then the wavelet coefficients of different resolutions are treated using different threshold values. Finally, the former results are reconstructed.

The steps in GPR image filtering are the following：

(1) Pre-processing filtering of GPR image.

(2) Decomposition of the pre-processed data.

(3) Threshold value processing of decomposed wavelet coefficients.

(4) Reconstruction of processed wavelet coefficients.

(5) After filtering treatment of reconstructed results.

4. FILTERING RESULT OF THE THEORETICAL MODEL

To test and verify the effect of multi-wavelet transform, we designed two models, one-point target and one-step target. First, we computed the theoretical image using GPR forward software of GPRMax[13]. The theoretical image was then mixed with noise. Finally, the image including noise was filtered using a multi-wavelet transform according to the above-listed steps.

4.1 Point target model

Figure 2 shows the forward modeling image of the point target. The image looks very clean except for the arc reflection. The forward image mixed with noise is shown in Figure 3. There are much irregular flocculent reflection which represent noise besides the arc reflection. And the processed result using a multi-wavelet filter is shown in Figure 4. After filtering, much of the irregular flocculent refection in figure 4 has been removed, and the image is clearer than that of figure 3. The arc reflection can be recognized easily compared with that in figure 3.

4.2 Step target model

Figure 5 shows the forward modeling image of a step target. The forward image mixed with noise is shown in Figure 6. And the result of filtered using multi-wavelet in Figure 7. The image changes from forward-calculation to that after mixed with noise and that after filtered using multi-wavelet are similar to that of punctate model.

GHM multi-wavelet filtering retained the character of the reflected signal and suppressed the noise effectively. After multi-wavelet filtering, the image became smoother.

5. FIELD DATA PROCESSING

A GPR image data of a single seawall is illustrated in Figure 8. The GPR signal was collected using a GSSI model SIR-20 GPR instrument (GECO-DMC, USA). The antenna of the SIR-20 integrates both emitting and receiving; its frequency is 100 MHz.

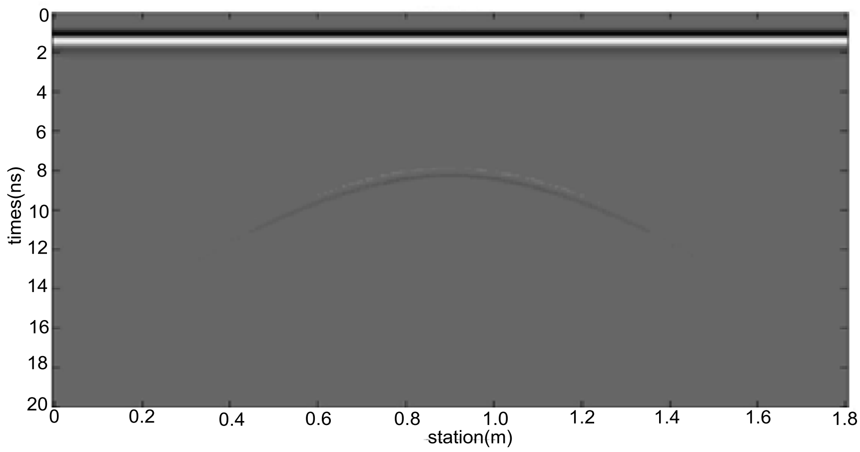


Fig. 2 Theoretical image of point target

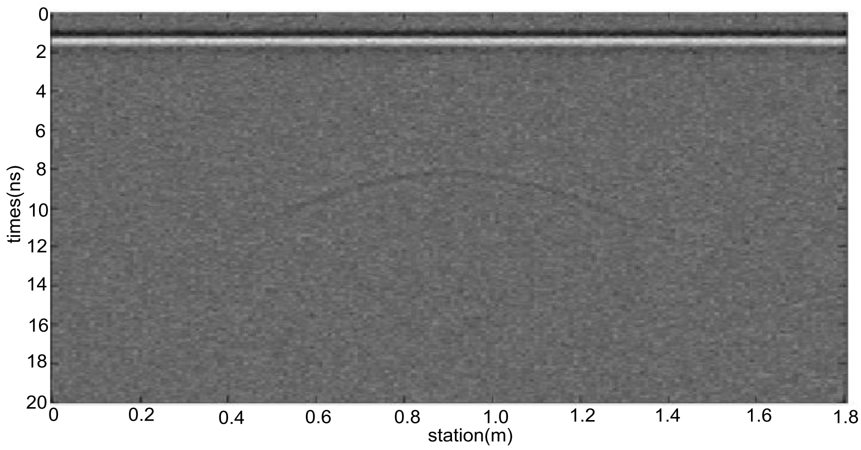


Fig. 3 Result of adding noise into Fig.2

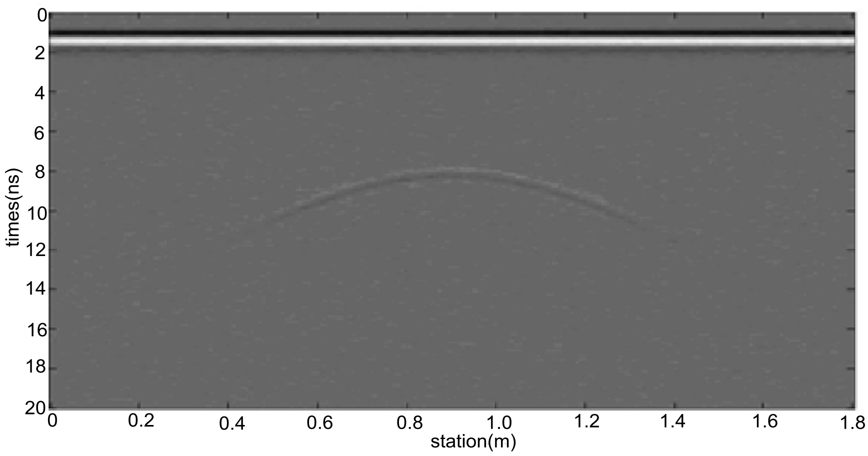


Fig. 4 Result of filtering

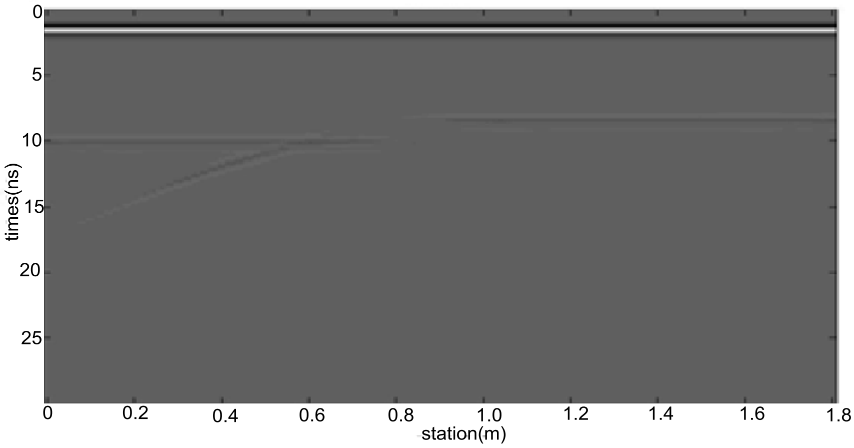


Fig. 5 Forward theoretical image of the step target

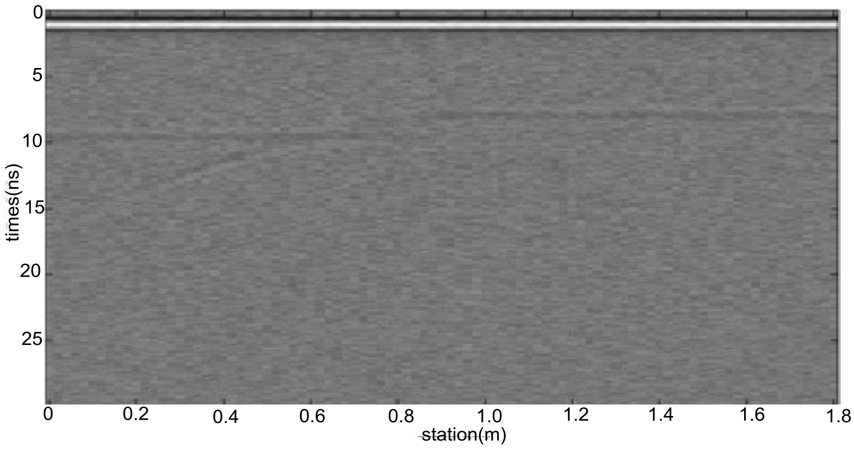


Fig. 6 Result adding noise into Fig.5

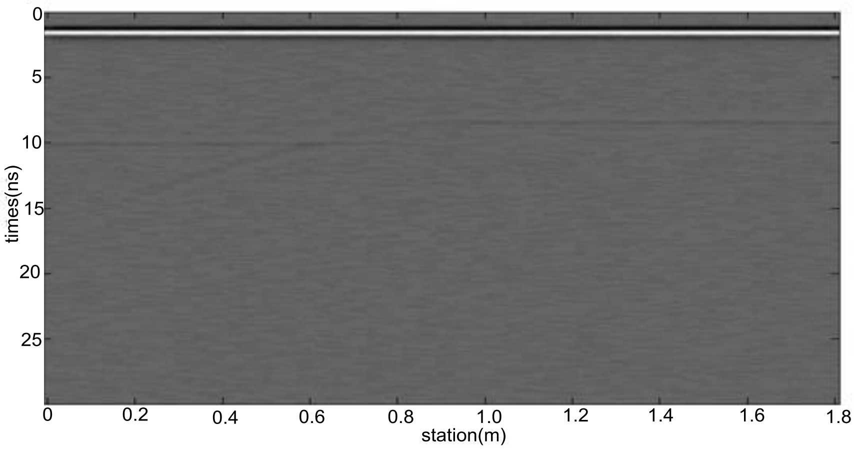


Fig. 7 Result of filtering

The surveying mode is continuous section, information on the abnormal zone is mixed with that of the background, and the stratification is not obvious. The image was filtered by means of multi-wavelet transform and the filtered and interpreted results are both shown in Figure 9. After processing by the multi-wavelet transform, stratification is more obvious than in the original image. The seawall is mainly formed by three layers, namely a dyke layer, riprap layer, and basement layer. The position and shape of the abnormal zone in the riprap was confirmed, where the water leakage is serious. The GPR filtering test result provided the basis for treatment of the water leakage.

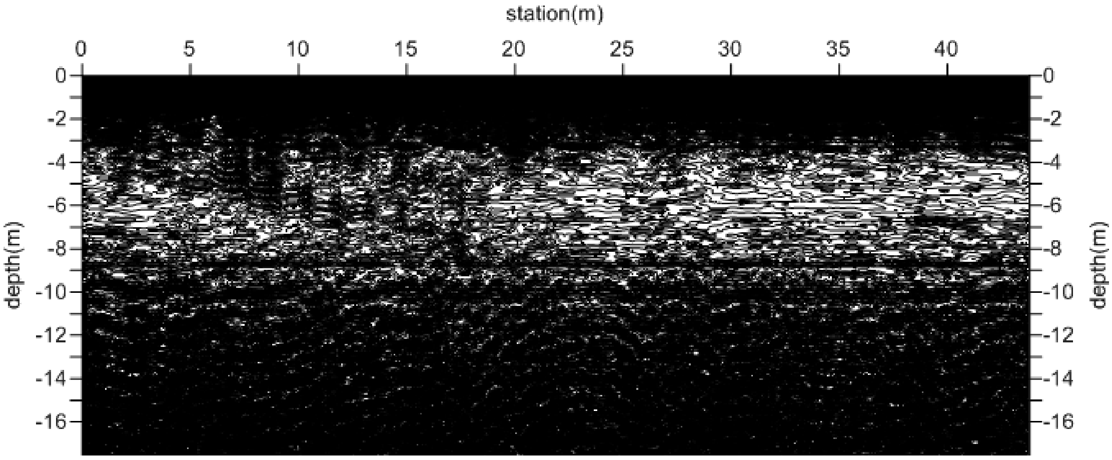


Fig. 8 Tested GPR image of top of seawall

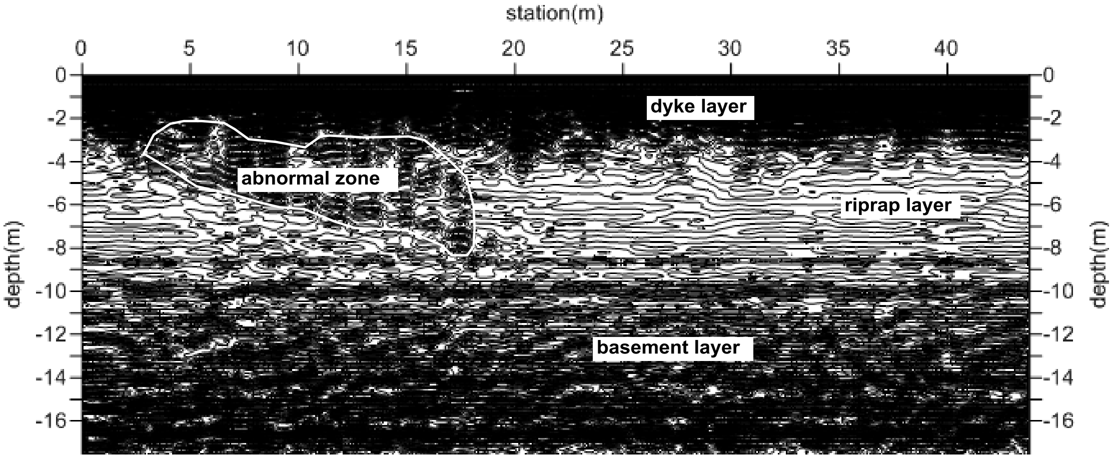


Fig. 9 GPR image of top of seawall after being filtered by multi-wavelet transform and interpreted result

6. CONCLUSIONS

In this paper, it focused on the de-noising of a GPR image by means of a multi-wavelet transform. The results were compared with the original image, i.e., the theoretical forward image, and it shows that the noise mixed with the initial image can be suppressed by the multi-wavelet filter.

The field GPR signals used in this study was collected at a single seawall experiencing long-term water leakage owing to construction defects. After filtering using the multi-wavelet transform, the noise was removed and the image features were rendered easier to recognize and interpret. The shape, location, and depth of the abnormal zone in the riprap layer of the seawall were confirmed, and, aided by this interpretation, and therefore, the required waterproofing treatment was recommended and has been completed smoothly.

7. ACKNOWLEDGEMENTS

This research is supported by the National Natural Science Foundation of China (No. 41374146).

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