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Method for Locating the Void Position between Asphalt Pavement Surface Layer and Base Layer Based on Radar Detection

Zhaojie Zhang[1], Hao Ma[2], Huan Zhang[1,*], Fei Yang[1], Zhaodi Yuan[1], Junrui Huang[1], Qirun Sun[1]
[1]*Shandong Transportation Institute, Jinan, Shandong, China*
[2]*Qingdao Transportation Development Group Co., Ltd, Qingdao, Shandong, China*
**Corresponding Author.*

Abstract: When faced with uneven settlement, consolidation, temperature and humidity changes, load and material factors, semi-rigid base asphalt pavement often experiences discontinuous contact between structural layers. The most commonly used non-destructive testing method for finding voids is the ground penetrating radar method, but the electromagnetic waves reflected by the voids between the asphalt pavement surface layer and the base layer are often masked by the interface reflection between the surface layer and the base layer, and it is difficult to accurately locate the size and position of the voids. In order to effectively detect and locate the void problem between the asphalt pavement surface layer and the base layer, this paper reduces the interference of interface reflection through horizontal filtering, and then uses an improved backward projection imaging algorithm for data processing to accurately identify the position and size of the void. The results indicate that this positioning method can accurately locate the location of road voids, which helps to timely repair and protect road structures, reduce maintenance costs, and ensure traffic safety and sustainable development of roads. This study provides important technical support for improving the accuracy of asphalt pavement detection, extending the service life of roads, and reducing traffic congestion.

Keywords: Asphalt Pavement; Radar; Road Surface Diseases; Get Empty

1. Introduction

The distribution of road surface diseases has a significant impact on road reconstruction and expansion decisions, and its detection results directly affect the technologies and plans adopted for reconstruction and expansion. As a biomimetic non-destructive testing device, ground penetrating radar has gradually been applied to road surface inspection [1-3]. In disease detection, the elimination of other interference sources in the road is particularly important, and error denoising can be achieved through parameter setting, post-processing, and other means [4]. Jia Hui et al. analyzed the common interference source images in road surface disease detection [5].

Using image processing technology to identify diseases is also an important research direction in the field of non-destructive testing. A large number of scholars have conducted extensive research on the processing of ground penetrating radar disease images using image processing techniques. Su Chang from Dalian University of Technology used an improved labeling method to quickly calculate the area of all isolated shapes in the radar B-Scan image. Then, he used a list line tracking method to quickly record the target and identified the pipeline target based on its convex and hyperbolic features in the ground penetrating radar image [6]. Chomdee has achieved good results in fast image recognition of underground mine targets based on pattern recognition and image processing methods [3]. Zaki used a combination of image processing and neural network technology to use a 2GHz IDS ground penetrating radar to determine the corrosion of steel bars in reinforced road surfaces, and the results were 100% consistent with the actual situation [7]. Yi an Cui utilizes central anomaly detection and fuzzy theory to recognize GPR images, which greatly improves detection efficiency by focusing only on the diseased part rather than the entire image [8]. Conroy used Matlab tools to 3D reconstruct the results obtained from ground penetrating radar and presented internal diseases from a semitransparent perspective [9]. In summary, the biggest challenge facing the use of ground penetrating radar to detect void diseases in asphalt pavement surface and base layers is that the electromagnetic waves reflected by void are often masked by the interface reflection between the surface layer and base layer, making it difficult to accurately locate the size and location of the void. This article presents a method for locating the void position between the asphalt pavement surface layer and the base layer. Firstly, the collected data is horizontally filtered to reduce the impact of reflected waves at the interface between the surface layer and the base layer on void recognition; Then, the horizontally filtered data is offset using an improved backward projection imaging algorithm to obtain the true position of the void.

2. Improved Backward Projection Imaging Technology

Back Projection Algorithm (BPA) is a classic synthetic aperture imaging method widely used in fields such as radar imaging, medical imaging, and geological exploration. The basic principle is based on the time delay superposition idea in signal processing. By compensating for the time delay of the echo data point by point and superimposing them, the echo signals at different times are matched with preset reference points, thereby achieving the acquisition of distance compressed signals and spatial inversion.

In specific operations, the backward projection imaging algorithm first needs to traverse and calculate each target point, determine its time delay based on the distance between the target and the transmitting and receiving points, and adjust the echo signals of each receiving point according to the time delay. Then, the signals from different receiving points are superimposed to obtain clear imaging results. This process requires independent calculations for each pixel, involving a large amount of convolution operations and iterative processing of multidimensional data. Therefore, the computational complexity of this algorithm increases exponentially, especially in high-resolution imaging or large-scale data processing scenarios, where the computation time will significantly increase.

Although the backward projection imaging algorithm has good imaging accuracy and can handle complex echo data well, its data processing efficiency is relatively low, and there is a problem of computational redundancy, which directly affects the real-time performance and operational efficiency of the imaging process, often requiring a long wait to obtain the final imaging results.

In order to improve computational efficiency, this paper proposes an improved backward projection imaging algorithm. The traditional backward projection imaging method requires calculating the delay time from the grid points in the partitioned area to all radar transmission positions, and then obtaining the energy superposition of the reflected signals of the grid points based on the delay time, which requires a large amount of computation. When radar signals propagate in a medium, they experience capability attenuation. As the propagation distance increases, the amplitude of radar reflection rapidly decays. Therefore, radar transmission points that are farther away from the grid point receive weaker radar reflection signals from that grid point, and can even be ignored. Therefore, this article only superimposes radar signals that are close to grid points, greatly reducing computational complexity.

The main steps of the improved backward projection imaging algorithm are as follows:

(1) Grid the imaging area and obtain the coordinates of all grid points;

(2) For a certain point A (i, j) in the mesh, the improved backward projection imaging algorithm only cares about the n radar reception signals adjacent to A (i, j) (Figure 1), and ignores the weak amplitude of the reflection signals received by the other radars from A (i, j). Assuming the distance from A (i, j) to R1 is S1, the round-trip travel time t1 can be expressed as:

$$t_1 = \frac{2S_1\sqrt{\varepsilon}}{c} \tag{1}$$

Among them, c represents the speed of light, and ε represents the dielectric constant of the underground medium.

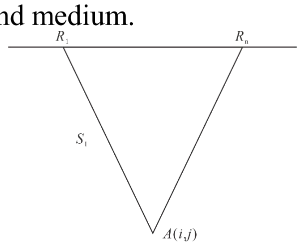

Figure 1. Schematic Diagram of a Point in the Grid and a Nearby Radar Receiving Point

(3) Interpolate the time series of the reflected wave signal received at the radar receiving point R1, find the amplitude value A1 of the radar reflected signal at time t1, and use the same method to obtain the amplitude values Ai（i=1,2,…,n） of all reflected signals at n radar transmitting points A(i, j). The value obtained by the improved backward projection imaging algorithm at A (i, j) is.;

(4) Repeat processes 2 and 3 to obtain the calculation results for all mesh points.

3. Numerical Simulation

In the radar detection of road surface diseases, numerical simulation is a key tool for analyzing the interaction between electromagnetic waves and road surface structures. It is used to study the propagation characteristics of electromagnetic waves in road materials, the influence of different diseases on signals, and the optimization of detection accuracy. It is an effective method to help study disease characteristics and signal propagation laws. Through numerical simulation, the impact of different types of diseases (such as voids, cracks, subsidence, etc.) on radar signals can be simulated to evaluate the detection capability of the radar system, optimize detection parameters, and provide guidance for actual detection.

Numerical simulation mainly uses numerical methods such as Finite Difference Time Domain (FDTD) and Finite Element Method (FEM) to solve the propagation equation of electromagnetic waves in various layers of the road surface. These methods can simulate the propagation, reflection, refraction, and other physical phenomena of electromagnetic waves starting from the transmitting antenna and passing through different material layers on the road surface, and simulate the echo signals received by the receiving antenna.

The center frequency of the radar antenna used in this article is 3GHz, the sampling window is 6 nanoseconds, and each channel consists of 1273 sampling points. Figure 2 shows the pavement structure model, assuming an asphalt layer (dielectric constant) within the depth range of 0-0.07m and a cement stabilized crushed stone layer (dielectric constant) within the depth range of 0.07-0.15m. T is the transmitting antenna, R is the receiving antenna, and the transmission and reception distance is 0.002m. There is a void filled with air at a depth of 0.064-0.7m.

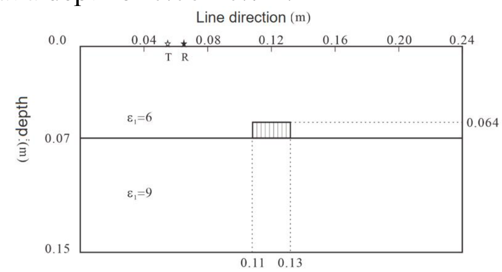

Figure 2. Pavement Structure Model

In the radar detection experiment of this article, the initial positions of the transmitting antenna TTT and the receiving antenna were 0.04 meters and 0.042 meters, respectively. The transmitting antenna and receiving antenna move synchronously to the right 79 times, with a movement interval of 0.002 meters, forming a series of radar detection data. Every time it moves, the transmitting antenna emits electromagnetic waves and the receiving antenna records the echo signal. The signals obtained through multiple movements can be used to construct two-dimensional B-scan images for analyzing road surface structures and potential disease features. Figure 3 shows the radar detection results, which significantly affect the visibility of other reflected signals due to the strong amplitude of the direct wave. Direct wave is the signal of electromagnetic waves that directly reach the receiving antenna from the transmitting antenna. Due to its short path and lack of attenuation through the dielectric layer, its amplitude is usually very strong, which easily suppresses the reflected signals in the medium, making the disease characteristics in the image less obvious. In addition, when the void area is located at the boundary of the dielectric layer, the reflected waves at the layer interface will further interfere with the reflected signals of the void area, making it difficult to clearly identify the location and range of the disease.

In order to effectively reduce the influence of direct waves and interface reflection waves, this paper introduces a horizontal filtering method. This method can suppress strong signals from direct waves and interface reflections to the greatest extent possible by smoothing the signal, thereby highlighting the disease characteristics in the reflected waves, especially the reflected signals in the void area. This processing method helps improve the clarity of the image and facilitates subsequent analysis of the range and depth of the void area.

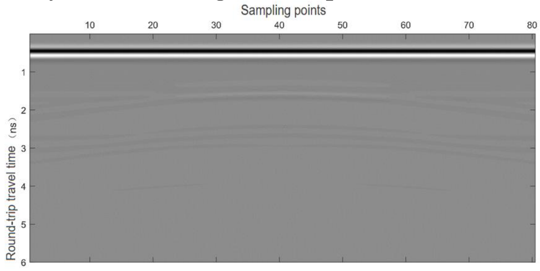

Figure 3. Ground Penetrating Radar Raw Data

4. Horizontal filtering method

Horizontal filtering is a smoothing technique commonly used in signal processing and image processing, mainly used to eliminate or weaken the influence of noise signals in order to highlight useful signal features. The basic idea is to replace the value of a certain point in the signal with the average of all values in the horizontal neighborhood of that point, in order to achieve a smoothing effect. In the field of signal processing, this local neighborhood is commonly referred to as a "window", also known as a convolution kernel or filter window.

The size of the window plays a crucial role in the horizontal filtering process. A larger window can effectively reduce high-frequency noise and make the signal smoother, but it can also cause details and abrupt changes in the signal (such as edge information or reflected waves) to be weakened or even erased. This is because larger windows increase the number of averaged signal points in the neighborhood, thereby reducing the contribution of high-frequency information (such as rapidly changing signals). Therefore, choosing the appropriate window size requires a comprehensive consideration of the characteristics of the signal and noise. If the window is too small, the noise suppression effect is limited and cannot significantly improve the smoothness of the signal; If the window is too large, although the noise can be sufficiently weakened, the signal characteristics will also be significantly affected, and even lead to the loss of useful information. Therefore, the setting of window size usually needs to be balanced based on specific signal characteristics and the nature of noise. For smoother signal and noise distributions, larger windows may be suitable; For signals containing more detailed features, small windows are better able to preserve useful information.

The value of a certain point can be replaced by the average of all values within a certain size of its horizontal neighborhood. This neighborhood is called a window in the field of signal processing. The larger the window, the smoother the output, but it may also erase our useful signal features. So, the size of the window should be determined based on the actual signal and noise characteristics. Figure 4 shows the result obtained through horizontal filtering. It can be seen from the figure that the influence of direct waves and horizontal interface reflection waves is greatly reduced, and the reflection wave signal in the void area is highlighted. However, it is difficult to determine the range and depth of the void area from Figure 4. Therefore, backward projection imaging technology is used here to obtain the range and depth of the void area. Figure 5 shows the results obtained by the improved backward projection imaging technique, and the area circled by the white box in the figure is the actual void area in the model.

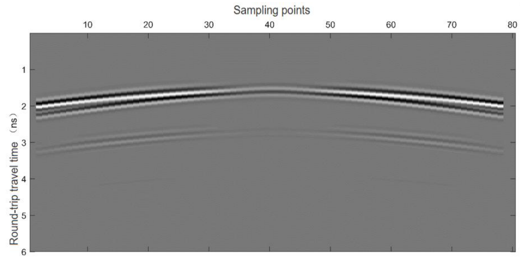

Figure 4. Ground Penetrating Radar Data after Horizontal Filtering

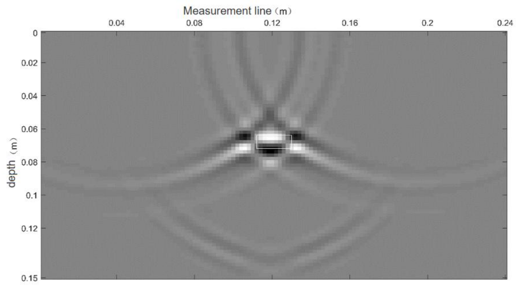

Figure 5. Improved Backward Projection Imaging Processing Results

The imaging results in Figure 4 show that the predicted void range and depth are basically consistent with the actual situation, verifying the effectiveness and feasibility of the proposed method in this paper.

5. Conclusion

This article proposes a method for locating voids between the asphalt pavement surface layer and the base layer, which is suitable for radar detection of road diseases. Horizontal filtering is applied to the collected data to reduce the impact of reflected waves at the interface between the surface layer and the base layer on void recognition; The horizontally filtered data is offset using an improved backward projection imaging algorithm to obtain the true position of the void. Effectively solved the problem of interface reflection interference in ground penetrating radar detection process, significantly improving the detection accuracy of void position and size. Helps to timely detect and repair pavement structural problems, extend road service life, reduce maintenance costs, and ensure traffic safety. This study provides new technical ideas for the development of non-destructive testing technology for asphalt pavement, which has important practical significance for improving the efficiency and accuracy of road detection.

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