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Applying ground penetrating radar to detect subway ballast voids

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ABSTRACT

The rapid development of subway construction in recent years has greatly eased the increasing traffic pressure in cities. The large-scale subway construction has also brought a series of engineering problems. Among them, the subway ballast void is one of the typical tunnel bed diseases, which poses a safety hazard to the tunnel during the operation period. At present, the detection methods for the subway ballast voids are not perfect enough. Therefore, it is urgent to detect and treat the ballast void. Based on GprMax software, this paper establishes a subway ballast voids model and carries out the forward simulation, and proposes a method of radar image feature and recognition of subway ballast void. At the same time, the feasibility of GPR in subway ballast voids detection is verified by engineering examples.

1. Introduction

In the long-term operation process, the subway has been affected by various factors such as long-term train vibration, hydrogeological conditions, construction quality, and surrounding engineering activities (Li, 2012). The subway ballast of some sections and the lower structure of the tunnel will gradually peel off and be voided, coupled with long-term erosion of water flow. The osmotic effect is easy to form a muddy mud phenomenon, which eventually causes the whole subway ballast to be voided. The harm of the subway ballast void directly affects the function of the subway ballast and the normal operation of the subway. For example, in November 2015, the subway from GuangAn to Daguan of Beijing Metro Line No. 7 went out of the station and the ballast was voided and cracked, and then developed rapidly. This caused the speed limit of the subway to be 45 km/h (Li, 2012).

At present, the detection methods of ballast void are not perfect enough. Conventional manual inspection can only record surface diseases such as cracking and water leakage, but cannot detect internal diseases. Coring by drilling or photographing by drilling may cause damage to the structure of the ballast bed and cause new diseases. Other geophysical methods, such as impact echo method, high-density electrical

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method, magnetic method, ultrasonic method and so on, are affected by the working environment and detection accuracy, which cannot be popularized and applied (Zhong, 2008).

The ground penetrating radar (GPR) method has the advantages of simple operation, fast detection and accurate results. In recent years, some experts have carried out a series of research work on the GPR tunnel detection:In 2006, Wang Kaikang explained the feasibility of the GPR in the detection of tunnel diseases by analyzing the application examples of the detection of underground water, softening layer and void in Shuiquanwan tunnel of Shuohuang railway (Wang,2006).

In 2012, Li Xiaokai, TongZhenghong discussed high-speed railway tunnel GPR method of nondestructive testing technology of antenna frequency selection, radar wave velocity calibration, mile marker, signal processing, image interpretation and the error analysis and solution, that the GPR can improve the efficiency of metro tunnel nondestructive testing and is conducive to eliminate the engineering quality hidden trouble (Li Xiaokai, Tong Zhenghong, 2012). However, there are not enough studies on ballast void, and the detection methods are not perfect enough.

In this paper, we will establish the model of the subway ballast void and use the GprMax software to simulate the GPR test results, and utilization of engineering examples to verify the applicability and accuracy of the GPR method applied to the subway track bed detection.

2. Methods and principle

2.1. Principles and characteristics of GPR

GPR sends high-frequency electromagnetic wave into the ground in the form of broad band short pulse through the antenna, Return to the ground after reflection from underground strata or target body and is received by the receiving antenna. The propagation path, intensity, and waveform of the high frequency electromagnetic wave vary with the change of the electrical characteristics and geometric form of the medium. By collecting, processing and analyzing the waveform, the spatial position and structure of underground interface or geological body can be determined. GPR has the following technical characteristics:

(1) Non-destructive detection can be applied to urban and construction engineering sites, with strong adaptability;

(2) It has strong anti-electromagnetic interference ability and can work in various noise environments in the city with little environmental interference;

(3)The detection depth and resolution are accurate, which can directly provide the implementation profile record map on site. The image is clear and intuitive, and the data acquisition, recording, storage, and processing are simple.

2.2. GPR image recognition

2.2.1. Color judgement

According to the above principles and characteristics, the ground penetrating radar image is set up with a black-and-white image and color image. Black-and-white images usually set positive voltage as white and negative voltage as black, so the sequence of positive waveforms is negative-positive-negative (black-white-black), while the sequence of negative waveforms is -negative-positive (white-black-white).

2.2.2. Applicability analysis

Urban Metro is usually composed of rails, fasteners, integral ballast bed, and segments. The ballast is constructed with integral reinforced concrete. The structure of metro ballast bed are shown in Fig.1. The purpose of the ballast is to support the sleeper and transmit the huge pressure on the upper part of the sleeper to the subgrade surface evenly. When the ballast and the structural floor are peeled off or even void in a large area, part of the ballast is in a suspended state, and only one between the ballast and the intermediate structural floor. There is air. Because the dielectric constant of concrete and air is different, there is a great possibility to detect the void of ballast by GPR in theory.

2.3. Forward modeling of subwayballast void

GprMax software is used in the forward simulation of ground penetrating radar. Based on the finite difference time domain method, the Maxwell equations with time variables are

Figure 1. Metro ballast bed.

differentiated by Yee grid, and the evolution process of electromagnetic field with time is given (Yee, 1996).

Most of the voids are gas layers produced by the non-compactness of concrete and ballast bed. In the detection of ground penetrating radar, there is strong reflection due to the presence of air in the void layer and surrounding rock mass. The model area is 3 m□0.5 m and the antenna center frequency is 900 MHz. The antenna is placed in the air area with a reserved thickness of 0.1m. The first layer is made of C30 concrete, The thickness of the second layer is 0.2m. The thickness of the second layer is 0.2m with C50 concrete. There is a void area of 0.05m in the first layer of concrete, and the medium is air. The dielectric constant of concrete is generally 4-9 and the air dielectric constant is 1. Because the electric loss is small, so the loss is neglected here. Each line collects 260 radar signals, and the antenna moving step is 0.01m. Importing the simulation data file of bad geological body model into GprMax software, and the forward model and result diagrams are obtained as shown in Fig.2.

From Figure. 2 - (b), it can be seen that there are about 200 scanning lines with obvious horizontal reflectors at 4.3ns, which is the reflection of the boundary of the void area. The symmetrical hyperbola on both sides is caused by the diffraction of rectangular corners. The horizontal reflection lines at 5ns and below are caused by the bottom reflection and multiple reflection of the void area. 4.3ns~5ns mainly show the adjacent accumulation of bright and dark layers, which is the void range.

2.4. Experimental results

In this experiment, a model of ballast void is made. The model is 3 m □2 m□0.5 m long, 55 cm wide and 20 cm deep grooves are set along the longitudinal direction of the model to simulate the central ditch. It is proposed to separate the 30 cm thick ballast bed from the 20 cm thick lower structure. The ballast bed is made of C30 concrete and the lower structure is made of C50 concrete. The ballast bed is hoisted to the upper part of the lower structure by a crane, and the height between the ballast bed and the lower structure is 10 cm. The cushion block of CM separates it. The concrete model and line location are shown in Fig.3.

The physical model and the instrument used in the field test are the SIR-3000 GPR of Laurel Company, USA. In this test, 900MHz antenna is selected, and the measuring line is arranged longitudinally. The measuring line passes through the void area.

The typical void situation of this model test is shown in Fig.4

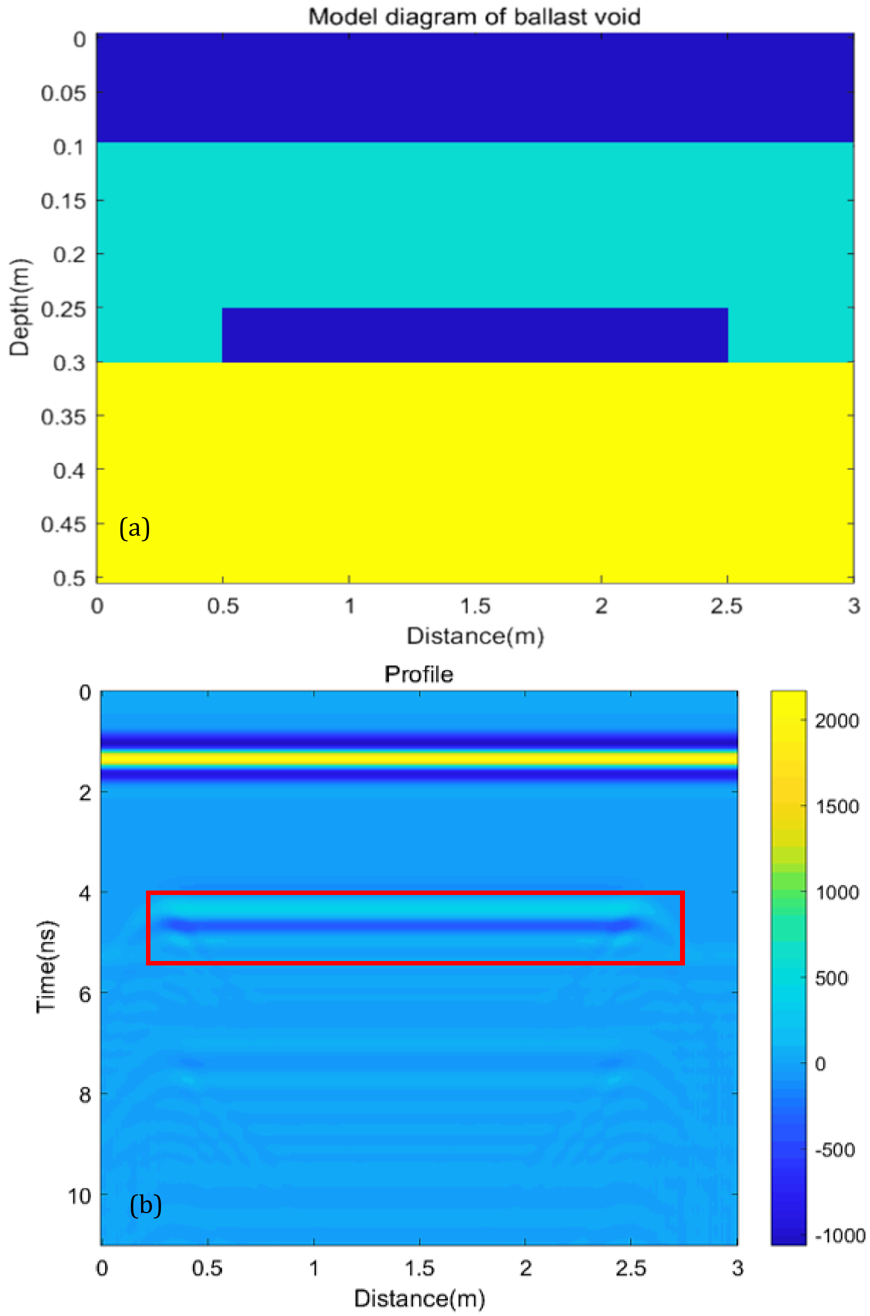

Figure 2. Numerical simulation. (a) Model of ballast void; (b) Result.

According to Fig.4, there are obviousreflective signals at depths of 0.29 m÷0.4 m, which are mainly shown as two bright layers with a black layer. The range is void area. The feature map is obvious, easy to distinguish, and the accuracy reaches centimeter level.

According to the comparison and analysis of the numerical simulation and physical simulation results, it can be concluded that:

(1) The characteristics of the void map are that there are obvious reflection signals at the boundary of the void area, which mainly show that the light and dark layers are adjacent to each other, and the areas of the light and dark layers are void areas.

(2) GPR has high accuracy in detecting the void of ballast bed, which can reach centimeter level, and can accurately determine the position and size of void.

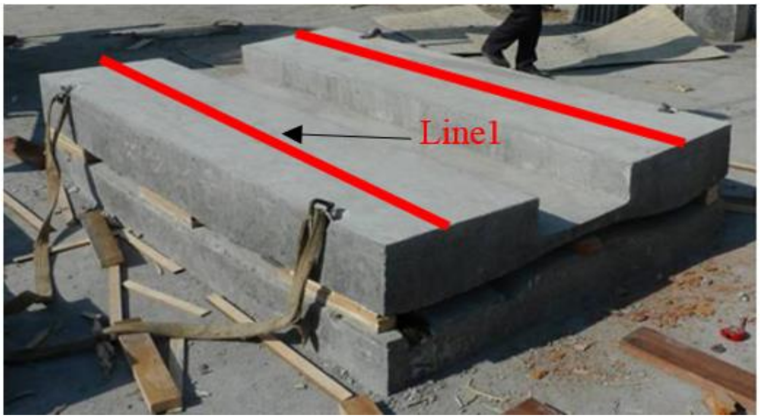

Figure 3. Concrete model and line location.

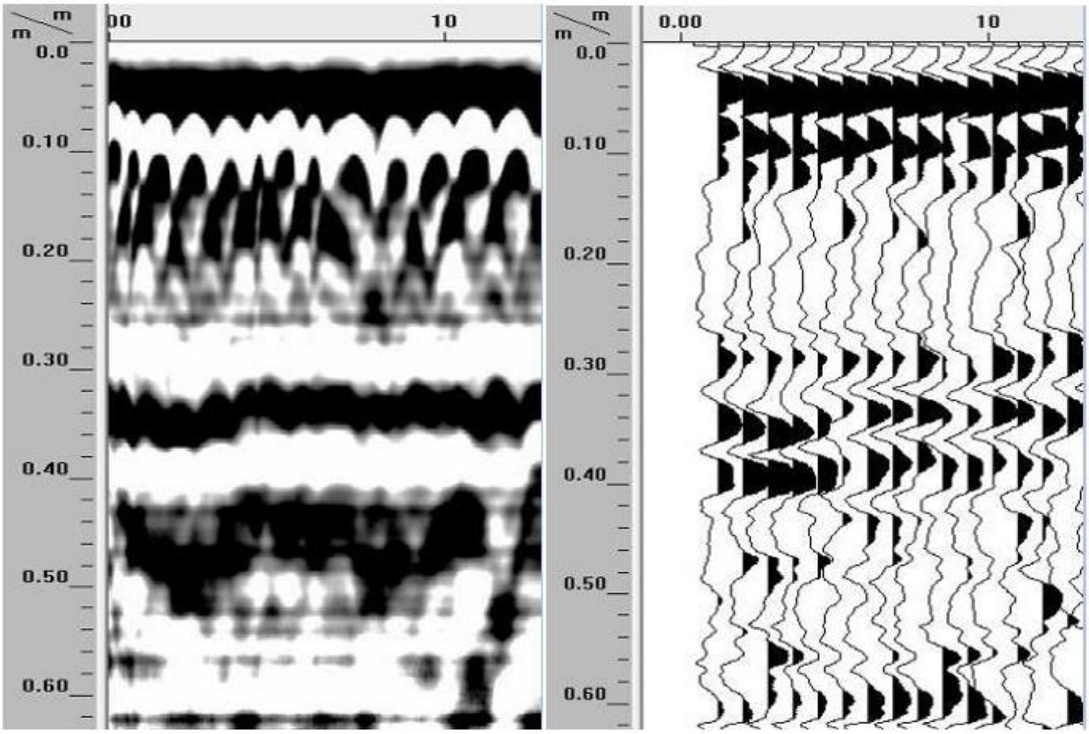

Figure 4. Characteristic map of void area of line 1.

3. Engineering example

3.1. Survey

Synthetic and experimental models show that GPR can detect the ballast void. In order to further verify that the ground penetrating radar can be applied to the detection of subway ballast voids, this study selected a subway section in Jiangsu Province as the test section. This section is an open-cut section. The main diseases of the selected 40m mileage section are cracking and peeling of the ballast bed and side-wall, surface cracks of the ballast bed. There are many seepage and frothing phenomena in different degrees, and the vertical settlement of the structure is large, which can be set as the test section. The measuring lines are laid out according to the requirements of the work, the parameters are calibrated, and the data are detected along the measuring lines and recorded in time.

3.2. Detection result

When moving along a measuring line, an anomaly is found in a certain position, and the detection is carried out along the vertical direction of the measuring line. The Diagram of vertical surveying line was shown in Fig. 5.

The radar detection chart is shown in Fig. 6. According to the radar waveform, the scanning image is a very clear black and white bright stripe, reflecting strongly, inclined to 20 degrees. The coaxial axis is linear and the phase of reflected wave is the same. According to the conclusion of model test, it is preliminarily judged that the abnormality here is ballast void. The cross section of the ballast bed in this area is shown in Fig. 7.

The shape of the ballast bed coincides with the inclined direction of the void layer in the detected image, so it can be judged that there is local void in the ballast bed.

Conclusion

(1) Then comparison between numerical simulation and physical simulation verifies the feasibility ofGPRfor metro track bed detection.

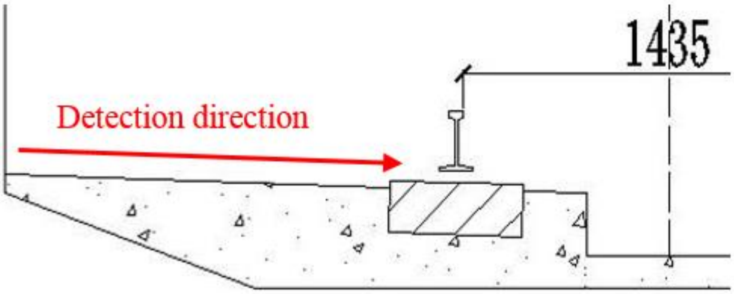

Figure 5. Diagram of vertical surveying line.

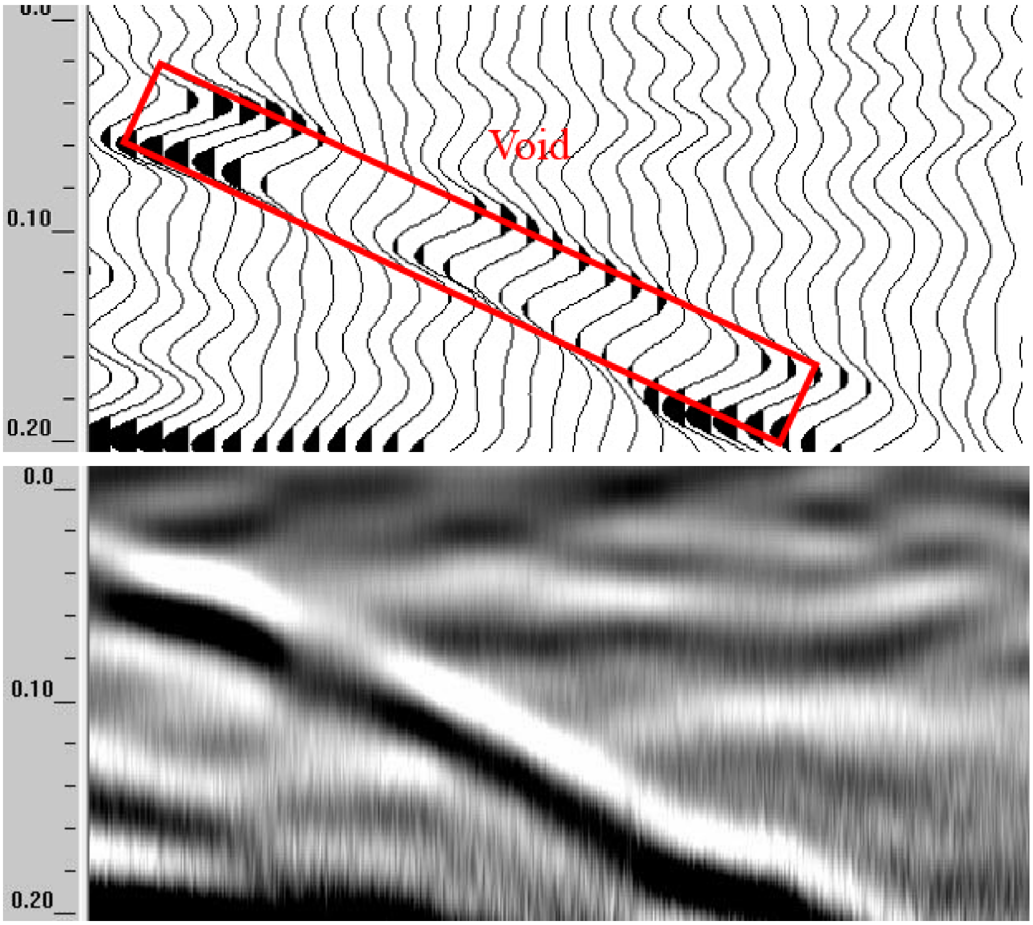

Figure 6. Diagram of radar detection. (a) Scanning; (b) Waveform.

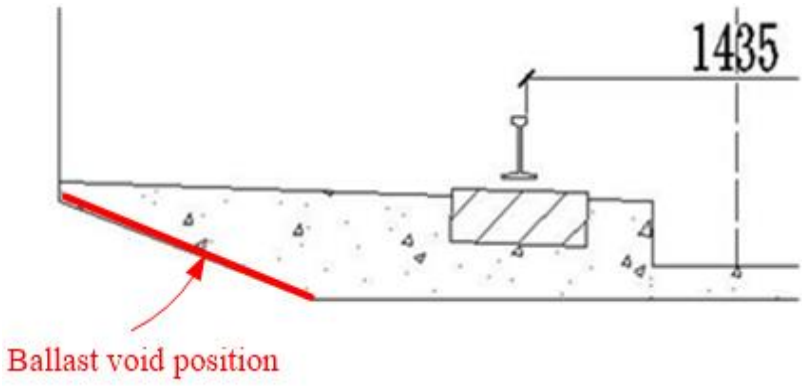

Figure 7. Position diagram of ballast void.

Through an engineering example of a metro section in Jiangsu Province, the accuracy of GPR in detecting the void of metro track bed is further verified.

(2) The radar waveform characteristic of subway track bed void mainly shows the accumulation of bright and dark layer adjacent to each other. The bright layer is the upper and lower boundary of the void area, which is more obvious in the waveform, and the whole range of bright and dark layer is the void area. In other engineering examples, the void disease can be identified by this feature map.

(3) The feasibility verification of GPRfor detecting the void of subway ballast bed can be extended to the detection of other diseases of ballast bed and can be applied to the detection of subway ballast bed in other projects.

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