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The Principle and Application of Ground Penetrating Radar in Highway Engineering

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Abstract

Highway roadbed has defects such as voids, collapses, and caves. If they are not discovered in time, the damage to the highway will affect people's travel safety. With the increasing scale and intensity of urban underground space resource development, urban road collapse accidents are common. In recent years, cities such as Beijing, Shenzhen, Guangzhou, and Nanjing have experienced urban road collapse incidents, which have affected traffic at the least and caused serious losses of life and property at the worst. For underground karst disasters, it is necessary to fully understand the geological information of karst. Construction and operation can be handled in a timely manner to avoid the occurrence of roadbed diseases. As a means of detecting geological conditions, ground penetrating radar has the advantages of high resolution, fast scanning speed, and intuitive images that are easy to interpret. In recent years, the non-destructive testing of ground penetrating radar has achieved good application results and accumulated a lot of engineering experience. This article first introduces the basic principles of ground penetrating radar, focusing on the common applications of ground penetrating radar in the field of highway engineering, mainly including the application of ground penetrating radar in engineering detection and quality evaluation. It analyzes the current problems existing in the application of ground penetrating radar in engineering and puts forward corresponding research ideas.

Keywords

Ground Penetrating Radar; Road Construction; Engineering Detection; Nondestructive Testing.

1. Introduction

Nowadays, China's infrastructure construction is becoming more and more complete. Highways, as one of the most basic facilities, have greatly improved the efficiency of national travel and have become an indispensable part of people's travel[1]. However, the geological conditions of many roads are complex and there are some unfavorable geological problems. However, the geological conditions of many roads are relatively complex, and there are some adverse geological problems, such as broken zones, water gushing, faults, cracks, karst caves, etc. Once these geological problems occur, they are likely to cause mud bursts, water gushing, landslides and other problems. Therefore, it is particularly important to find a convenient and accurate detection and prediction method[2].

Zeng Sheng, Li Zhencun and others used air-coupled antenna ground penetrating radar and modified the layout method of high-density electrical electrodes and Rayleigh wave detectors to achieve rapid detection of highway subgrade diseases, but did not mention the specific detection speed. This method is based on the complementarity of detection indicators and detection objects of different detection methods, and adopts multi-sensor fusion data acquisition and processing methods to achieve comprehensive detection of subgrade diseases.

Finally, through the comprehensive processing platform for subgrade diseases, the joint interpretation of subgrade disease detection data and the visualization and grid display of subgrade diseases are realized[3]; Xie Zhaohui, Wu Xiaoping, Sun Qihua and others applied geological radar to non-destructive testing of highway roadbeds[4-6]; Fan Zhaoping and Wu Xiaopeng applied geological radar to frozen soil roadbeds, which can quickly explore permafrost, divide stratigraphic boundaries and determine the distribution of permafrost[7-8]; Wu Tianjun and others combined geological radar with transient electromagnetic method and applied it to the diagnosis of water pipeline leakage on a highway in Shanxi[9].

Although different scholars use different methods to detect diseases, ground penetrating radar is currently recognized as an effective method for detecting roadbed diseases, and it has been listed as a routine detection method in some large and medium-sized cities[10].

In recent years, there are many methods for non-destructive testing of highways, and the corresponding technologies are becoming more and more mature. Ground penetrating radar technology was first used in road testing in Denmark, Sweden and other countries in the early 1980s. Since then, ground penetrating radar has been widely used in business. The research in China on ground penetrating radar began in the 1970s. In the 1990s, some scientific institutes thought of using ground penetrating radar technology in road disease research. Many experiments were carried out and the results were very good. This also laid a certain foundation for the application of ground penetrating radar in my country[11]. This paper will use ground penetrating radar as a detection method to detect the specific geological information of highway caves.

2. Principle and Introduction of Ground Penetrating Radar

The ground penetrating radar detection system consists of a transmitting antenna, a receiving antenna, and a data storage control system. The ground penetrating radar transmitting antenna emits high-frequency electromagnetic pulses with a certain center frequency, which are vertically incident on each underground structural layer. The electromagnetic waves will be reflected at the electrical interface and abnormal body. The schematic diagram of the working principle of the ground penetrating radar is shown in Figure 1. By moving the transmitting antenna and the receiving position, the profile data of the entire survey line is collected for imaging. Then, the spatial position, electrical properties, structure and geometric shape of the target body under the highway subgrade are analyzed and inferred based on the amplitude, two-way travel time, frequency and other characteristics of the received signal. As shown in Figure 2, on the profile of the ground penetrating radar, the interface of the stratum and the arc abnormal interface of the cave are shown.

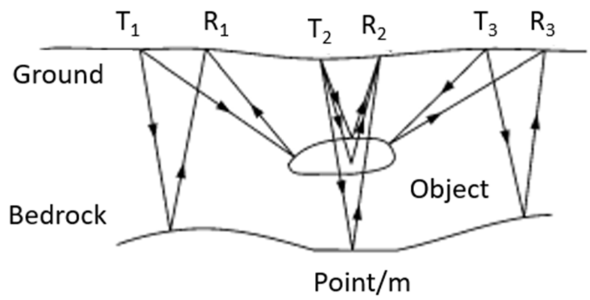

Figure 1. Schematic diagram of ground penetrating radar detection principle [11]

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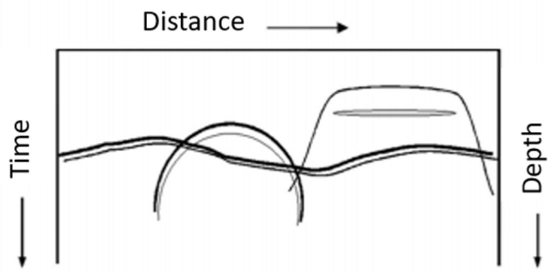

Figure 2. Schematic diagram of ground penetrating radar data imaging[1]

3. Major Highway Engineering Diseases

Due to regional and temporal differences, as well as uneven rainfall, different vehicle speeds and volumes, and different bed soils, the existing highway subgrade conditions are very complex, and the types, distribution forms, and development levels of defects are complex, diverse, and random, which increases the difficulty of detecting existing highway subgrades. The main purpose of subgrade defect investigation is to conduct a census of the old subgrade conditions and the degree of defects; the main task of the investigation is to find out the number, length, width, and distribution of subgrade cracks and subsidence, the topographic and geological conditions around the subgrade, the lithology, soil and rock content, and apparent density of the old subgrade filling, and the overall stability of the subgrade, so as to provide a reference for subgrade detection and the design and construction of subgrade defect treatment. The classification of common highway subgrade engineering defects is shown in Table 1 [2].

Table 1. Defects of existing highway subgrade engineering

Disease type	Main feature
Roadbed cracks	Roadbed cracks are often accompanied by local subsidence, and road slabs may crack or break.
Roadbed subsidence	The settlement of the left and right roadbeds is inconsistent, the road surface is uneven, and there are even cracks and depressions.
Roadbed filling	It is a hidden disaster that is not easy to detect and requires analysis of the rock properties of the roadbed filler.
Roadbed stability of high fill sections	It is a hidden disaster that is not easy to detect and requires analysis of the rock properties of the roadbed filler.

4. Ground Penetrating Radar Image Characteristics of Underground Damage in Roads

The processed two-dimensional data is processed using the inverse scattering imaging method and the offset method to establish a true amplitude reconstruction algorithm, and then fitted into a three-dimensional data body for targeted cutting, so as to obtain a variety of information such as the outline and position of the underground anomaly or target body, and obtain reliable detection results.

However, to accurately interpret the detection results, it is also necessary to clarify the radar image characteristics of various disease bodies, mainly including the wave group morphology, amplitude, phase and frequency characteristics of the radar spectrum of disease bodies such as cavities, voids, loose bodies and water-rich bodies. The multiple waves of cavities are developed, the diffraction waves are obvious, and the overall amplitude is strong; the wave group characteristics of voids are similar to the development of plate-like multiple waves, which may be accompanied by obvious phase axis shedding characteristics, and the overall amplitude intensity is also strong; the waveform of loose bodies is chaotic, the phase axis is disordered, the multiple reflections are obvious, and the overall amplitude intensity is also strong; the top of the hydrophobic body forms a continuous reflection wave group, the phase axis is continuous, the reflection energy is strong, and the energy decays rapidly, but the top of the water-rich body is strong and the energy decays rapidly. For the four types of diseases, cavities, voids, loose bodies and water-rich bodies, their phases are all the same as the incident wave.

5. Application of Ground Penetrating Radar in Highway Engineering

5.1. Structural Layer Thickness Detection

The thickness of the pavement structure layer can be calculated by the formula based on the propagation time of the electromagnetic wave in the pavement structure layer and the propagation speed of the surface wave in the structure layer. Therefore, the key to thickness detection lies in the echo time of the structure layer interface and the determination of the propagation speed of the electromagnetic wave in the structure layer. Figure 3 is a schematic diagram of the principle of ground penetrating radar detection of the thickness of the pavement structure layer. In the figure, A_0, A_1, and A_2 represent the amplitude of the reflected wave generated by the electromagnetic wave at the interface between the air and the surface layer, the amplitude of the reflected wave generated by the electromagnetic wave at the interface between the surface layer and the base layer, and the amplitude of the reflected wave generated by the electromagnetic wave at the interface between the base layer and the soil base; the propagation time Δt_1 from A_0 to A_1 is the round-trip travel time of the electromagnetic wave in the surface layer, and the propagation time Δt_2 from A_1 to A_2 is the round-trip travel time of the electromagnetic wave in the base layer.

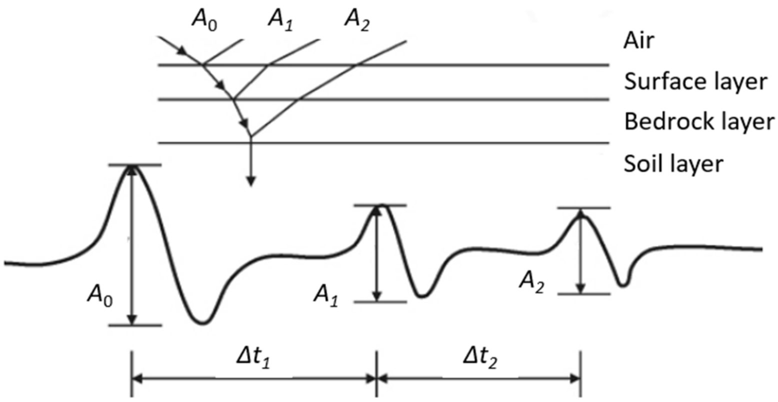

Figure 3. Schematic diagram of the structure thickness detection principle of ground penetrating radar [12]

The thickness of the structural layer can be calculated according to the following formula:

$$H = \frac{c}{\sqrt{\varepsilon_r}} \cdot \frac{\Delta t}{2} \tag{1}$$

In the formula: H represents the thickness of the structural layer,Δt represents double-layer travel time of electromagnetic wave propagation,c represents the speed of light, ε_r represents the relative dielectric constant of the material in the structural layer.

The main parameters that need to be determined in this calculation formula are ε_r and Δt. Δt can be determined based on the time difference of the reflected wave echo from the upper and lower interfaces of the target structure layer of the radar signal. The relative dielectric constant cannot be guaranteed to be a constant value in practical applications. It can be obtained by the change in the amplitude of the reflected wave, or it can be measured by a dielectric constant meter during the construction process, or by indoor velocity calibration of the cored rock and soil in the borehole. After determining the double-layer travel time and relative dielectric

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constant of the structural layer, the thickness of the structural layer can be calculated according to formula(1).

5.2. Void and Void Identification

During the long-term use of highways, due to the influence of various factors, defects such as voids between the base layer and the fill layer, cavities under the road surface, and peeling of the asphalt layer will occur, which will affect the service life of the highway. Ground penetrating radar can effectively identify these engineering defects.

The principle of GPR for identifying voids is based on the large difference in relative dielectric constant between the void medium and other surrounding media. The void anomaly on the GPR profile usually presents a hyperbolic shape, especially when the void medium is air and the void depth is not large, the void will show obvious abnormal characteristics on the radar profile. The identification of void layers is mainly based on the principle that the polarity of the reflected wave generated at the upper and lower interfaces of the void layer is reversed. As shown in Figure 4, the left image shows that there is a void under the rigid pavement, and the right image is the corresponding reflected wave waveform. Among them, reflected wave A is generated by the reflection of the interface between concrete and air, reflected wave B is formed by the reflection of the interface between air and base layer, and reflected wave C is the superposition of reflected wave A and reflected wave B. The waveform finally displayed on the GPR instrument is reflected wave C. Due to the different positive and negative reflection coefficients of reflected wave A and reflected wave B, the phase (polarity) of the two reflected waves is reversed. By determining the time difference of the reflected waves, the relevant parameters of the void can be calculated by the formula[12].

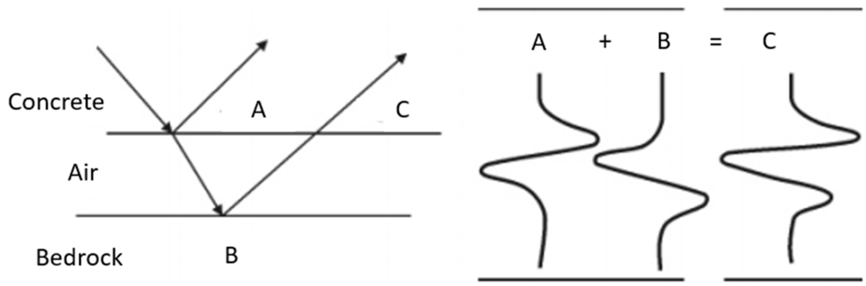

Figure 4. Schematic diagram of the principle of ground penetrating radar for air gap identification [12]

5.3. Tunnel Advanced Geological Prediction

Ground penetrating radar can predict and forecast unfavorable geological structures such as faults, cracks, broken zones, cavities, and groundwater in the surrounding rock in front of the tunnel face, and can provide a basis for the construction party to reasonably arrange the excavation plan, excavation speed, and support measures. When there are unfavorable geological bodies such as faults, broken zones, or cavities in the rock strata in front of the tunnel, there is a large electrical difference between the unfavorable geological bodies and the intact surrounding rock, and there is a significant change in the dielectric constant, forming a strong reflection anomaly with discontinuous phase axis of the reflection wave on the radar profile.

5.4. Tunnel Lining Quality Inspection

The content of tunnel lining quality inspection includes tunnel lining thickness, unfilled empty areas behind lining, large gaps between composite linings, and the degree of airtightness of lining concrete. The inspection principle of tunnel lining thickness is similar to that of structural layer thickness. The lining thickness is calculated by determining the propagation speed of electromagnetic waves in the lining or the relative dielectric constant of the lining medium and the two-way travel time of electromagnetic waves using formula(1). Unlike the inspection of structural layer thickness, the lining thickness is often small. Therefore, although there may be a large electrical difference between the lining and the surrounding rock, the abnormal display on the radar reflection wave profile is not very obvious. Data processing and comparison with field data are required for careful identification. The principle of tunnel lining void detection is similar to the aforementioned highway roadbed void detection principle. The distribution of the void and its distance to the outer surface of the lining can be determined by using the correlation waveform characteristics of the two strong reflection waves generated by the upper and lower interfaces of the void. However, sometimes the anomaly formed by the void is similar to the anomaly formed by the local bulge of the surrounding rock. Therefore, when confirming whether it is a void, the abnormal morphology must be carefully analyzed and confirmed. During the construction process, the empty areas formed by over-excavation or collapse should be backfilled, and ground penetrating radar has obvious corresponding characteristics for the degree of density of the backfill. In the backfilled area with insufficient density, a strong reflection signal with discontinuous reflection phase usually appears on the ground penetrating radar image, which can be used as a feature to judge the backfill of the insufficient density area. When using ground penetrating radar to evaluate the density of concrete, the lining concrete can be divided into dense chamber and relatively loose chamber according to the waveform change characteristics of the ground penetrating radar reflection wave. In the case of dense chamber, the phase of the reflection wave is stable, and there is no strong amplitude chaotic reflection in the layer. In the case of loose chamber, the amplitude of the reflection wave changes greatly, the phase is unstable, and the waveform is chaotic[12].

5.5. Steel Bar Distribution and Concrete Cover Thickness Detection

As with the detection of other targets, the large electrical difference between steel bars and the surrounding medium provides good detection conditions for ground penetrating radar. When the electromagnetic wave emitted by the transmitting antenna passes through the steel bars, a strong reflection amplitude will appear, and the reflection phase is relatively stable. At the same time, attention should be paid to the selection of the center frequency of the ground penetrating radar to prevent confusion in the identification of adjacent targets caused by low lateral resolution.

6. Conclusion

This paper mainly introduces the common applications of ground penetrating radar in the field of highway engineering. From the current application effect, ground penetrating radar has the advantages of high resolution, high efficiency and convenience in the field of engineering detection, which is different from other geophysical methods. It has achieved good application results and has been widely used in a large number of different engineering fields. At the same time, in order to achieve more accurate interpretation effects and higher efficiency, further in-depth research can be carried out on ground penetrating radar instruments to optimize the detection depth and resolution of ground penetrating radar. Engineering practice has proved that ground penetrating radar can achieve good exploration results regardless of whether the karst caves in the highway subgrade are filled. Ground penetrating radar has the characteristics of high precision and high efficiency. In the field of disaster diagnosis of highway subgrade, it has a wide range of applications for shallow target anomalies. However, in the actual test process, the ground penetrating radar method may have certain errors in the detection of the specific location of the bad geological body, and it is difficult to accurately obtain the value. Therefore, we also need to further study how to improve the accuracy of the detection results of ground penetrating radar in these engineering fields.

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References

[1] J. Li: Application of geological radar in detection of karst caves in highway subgrade, West-China Exploration Engineering, (2022) No.5, p.86-88.

[2] C.Q. Wang, Z.L. Wu, Y.F Deng, et al: Detection methods for existing road subgrade engineering and project analysis, Advances in Science and Technology of Water Resources, Vol. 36 (2016) No.2, p.69-73.

[3] S. Zeng, Z.C. Li, J. Zhao, et al: New technology for rapid and non-destructive comprehensive detection of roadbed diseases in operation, Journal of Changsha University of Science & Technology(Natural Science), Vol. 10 (2013) No.2, p.1-7+21.

[4] Z.H. Xie, J.M. Li: Application of Ground Penetrating Radar Technology in Road Subgrade Defect Detection, Geology and Exploration, Vol. 43 (2007) No.5, p.92-95.

[5] X.P. Li: Application of Ground Penetrating Radar Technology in Highway Disease Detection, Shanghai Geology, (2008) No.2, p.54-56.

[6] Q.H Sun: The study of nondestructive testing applied in subgrade quality inspection (MS., Chongqing Jiaotong University, China 2010), p.1.

[7] Z.P. Fan, L.H. Zhang, X. Lu: Application study on ground penetrating radar for highw ayengmeerig exploration n pem afrost region, Geotechnical Investigation & Surveying, (2010) No.3, p.91-94.

[8] X.P Wu, Y.L. Wei, J.P. Zhang: Study on the Application Effect of Ground penetrating Radarin Permafrost Engineering Geological Investigation, China Earthquake Engineering Journal, Vol. 35 (2013) No.2, p.240-245.

[9] T.J. Wu: A dissertation on the application of comprehensive geophysicaltechnique in the detection of roadbed diseases, Communications Science and Technology Heilongjiang, (2018) No.7, p.4-5.

[10] Z.H. Wu: Application of geological radar technology in highway disease detection, Engineering Technique, (2016) p.230.

[11] Z.T. Li, Z.L. Wu, Y.F. Deng: Research on the application of geological radar in highway disease detection, Subgrade Engineering, (2015) No.1, p.91-95.

[12] R. Deng: Application of Ground Penetrating Radar in Highway Engineering Detection, Sichuan Architecture, Vol. 40 (2020) No.3, p.88-90.