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Application of ground penetrating radar for estimating the water content of road structure

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Abstract: *Due to the influence of construction quality, material aging, uneven settlement of foundation and other factors, cracks and water accumulation often occur in the road structure layer. The accumulated water will directly affect the overall quality, service life and normal functions of roads, and adversely affect the integrity, stability and driving safety of pavement structures. In this paper, based on the characteristics of high efficiency and nondestructive detection by ground penetrating radar, and relying on an actual road project in Anyuan County, Ganzhou City, and based on theoretical analysis, it is proposed to use ground penetrating radar to obtain measured data to estimate the water content of road structure. The application and research status of ground penetrating radar detection technology at home and abroad were analyzed. Based on Maxwell basic equation, the basic principle and field detection technology of ground penetrating radar were analyzed. Based on the actual road engineering, the water content of road structure layer was estimated theoretically and verified by core drilling. The results show that it is feasible to estimate the water content of road structure layer by using ground penetrating radar, which can provide relevant reference for nondestructive testing of road structure.*

Keywords: *Ground penetrating radar, Road engineering, Water content, Field detection, Estimation*

1. Introduction

In recent years, with the gradual improvement of domestic highway traffic network, a large number of highway projects have been built and used. Practice shows that there are various types of unfavorable geological bodies such as cavities, fissures, water and faults in the stratum. The existence of water will adversely affect the integrity and stability of pavement structure, and even endanger the overall driving safety of pavement. Although the method of drilling can quickly identify the water in the stratum, it will destroy the original integrity of the pavement, so it is urgent to find a rapid and effective detection method without damaging the structural integrity of the pavement.

At present, geological analysis and physical exploration are the two main geological advanced detection technologies. Geological analysis method has a wide range of applications, but it has a strong dependence on the accuracy of survey data [1]. Therefore, geological analysis method is often combined with physical exploration method [2]. According to the prediction distance, the physical exploration method can be divided into short-distance prediction method (detection distance is less than 30 meters) and long-distance prediction method (detection distance is more than 100 meters). Among the long-distance prediction methods, the seismic wave reflection method is the most widely used, but its operation is complex, the equipment is heavy and the resolution is low. Among the short-range forecasting methods, the ground penetrating radar method is the most widely used.

The effective detection length of ground penetrating radar is generally 20-35m, which has the advantages of high precision, nondestructive detection and efficient positioning [3]. In recent years, many experts and scholars at home and abroad have done a lot of research on ground penetrating radar advanced detection and achieved certain results. However, most of the research mainly focused on the detection of voids, cracks and loose areas in the structural layer, and less on the detection and identification of accumulated water in the structural layer, while the research related to the detection and identification of water content is even rarer. In addition, for the water in the road structural layer, the current measurement method is still based on the traditional core drilling method, but this method will seriously damage the integrity of the structural layer itself and accelerate the invasion of external

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seepage water, which is an important problem at present.

Therefore, based on the basic theoretical analysis of ground penetrating radar detection, this paper, relying on an actual road project in Anyuan county, Ganzhou City, obtains the measured images through field detection and calculates the water content in the road structure layer by using the theoretical estimation method.

2. Project Introduction

2.1. General Introduction

The road is located on the south side of Jiulong avenue in Anyuan county, and the traffic is extremely convenient. The original landform belongs to alluvial landform. The original site is cultivated land, vegetable fields and houses, with slightly undulating terrain. The site elevation is 290.5-294.8m, and the height difference is about 4.61m. The stratum is mainly composed of quaternary artificial miscellaneous fill and pebble. It is found that the rock and soil layers in the drilling site can be divided into 6 layers, and the sequence of each layer is basically clear. No unfavorable geology such as landslide, mined-out area, dark shore, land subsidence, karst, etc., and no underground burial objects such as ancient tombs, etc. were found within the survey scope.

2.2. Special Soil

It is mainly cultivated soil and miscellaneous fill, which is backfilled by building wastes such as bricks and cement produced by house demolition. Completely weathered and strongly weathered rock strata are widely distributed in the site, which tend to soften and disintegrate after being soaked in water, with a sharp decrease in strength and poor stability. There are no soluble rocks, voids, weak rock layers, active faults and fracture zones within the main bearing stratum of the foundation.

2.3. Underground Water

Underground water is mainly diving water and bedrock fissure water. The diving water level varies greatly with seasons and topography. Bedrock fissure water is controlled by the development degree, connectivity and rock structure of joints and fissures, and its hydraulic force field and seepage state are obviously anisotropic. The underground water is non-corrosive and will not cause corrosion damage to concrete and road structure layer.

3. Detection Principle of Ground Penetrating Radar

3.1. Maxwell Basic Equation

When the electromagnetic wave is incident on the medium interface, refraction and reflection will occur. Therefore, ground penetrating radar makes use of this propagation characteristic to detect the target. Electromagnetic waves are formed by alternating electromagnetic fields in the air. Unlike mechanical wave, electromagnetic wave can propagate without medium, so it belongs to medium-free wave. Electromagnetic wave propagation in medium must satisfy Maxwell equations.by Eq.1.

Constitutive relation expresses the relationship among the parameters in Maxwell equations. When the electromagnetic field propagates in natural or artificial medium, there may be polarization, cross polarization and magnetization. Therefore, the electromagnetic constitutive relation can be expressed by Eq.1 [4].

$$\begin{cases} H = M \bullet E + Q \bullet CM \\ CD = P \bullet E + L \bullet CB \end{cases} \tag{1}$$

Where *P*, *Q*, *L* and *M* are all third-order square matrices, and *C* is the speed of light in the air.

3.2. Propagation Velocity of Electromagnetic Wave

According to the standard wave equation, the propagation velocity of electromagnetic wave can be obtained. Experiments show that the change of dielectric constant and permeability of medium will

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directly affect the propagation velocity of electromagnetic wave, namely, with the increase of dielectric constant, the velocity will decrease gradually, as shown in Figure 1.

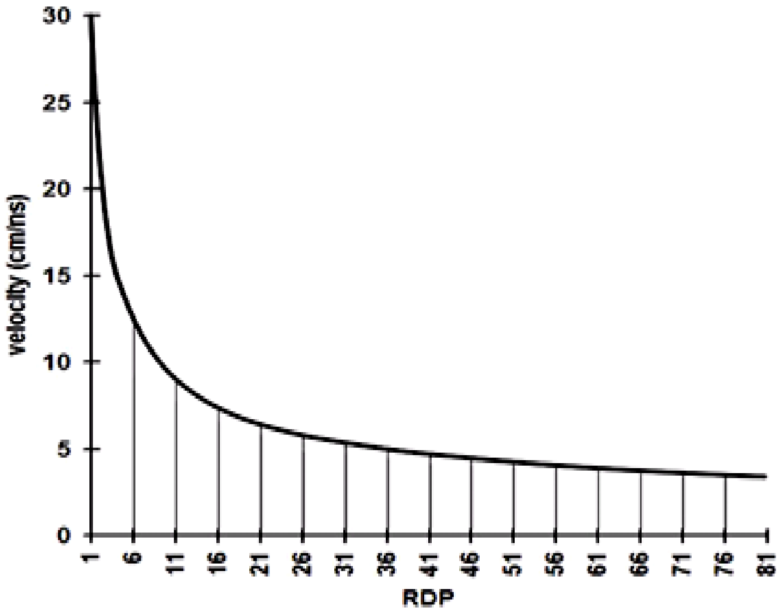

Figure 1 The velocity variation law of electromagnetic wave

3.3. Display Model of Detection Data

When the excitation methods used in field detection are different, the data display will be different, and when different programs and software are used for analysis, the data display will also be different [5].

According to the different scanning time distribution, detection data display models can be divided into two different models, namely, single data and multi-channel data display model. Single-channel data display model is used for point-scan detection, while multi-channel data display mode is used for continuous line-scan detection. In practical engineering applications, continuous line-scan detection is more widely used than point-scan detection. Figs. 2 and 3 show two different data display models. These two pictures are only used to illustrate the display models, so the vertical and horizontal coordinates are omitted.

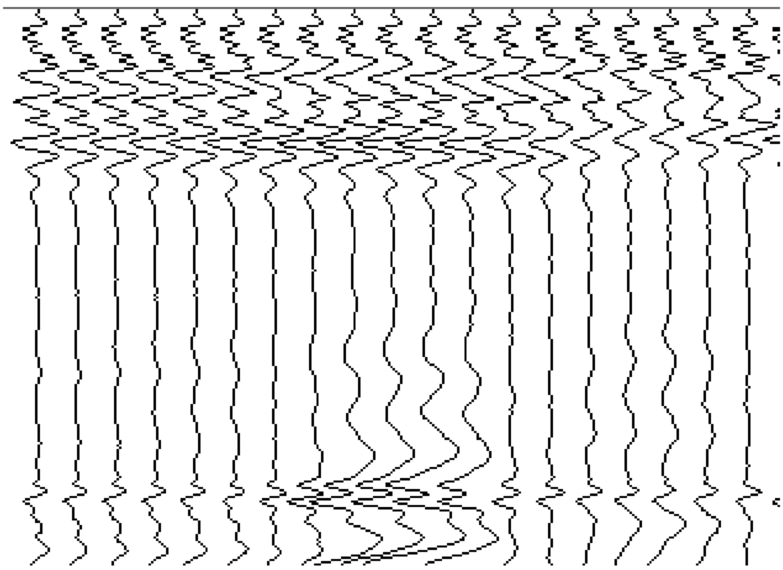

Figure 2 The multi-channel data display model

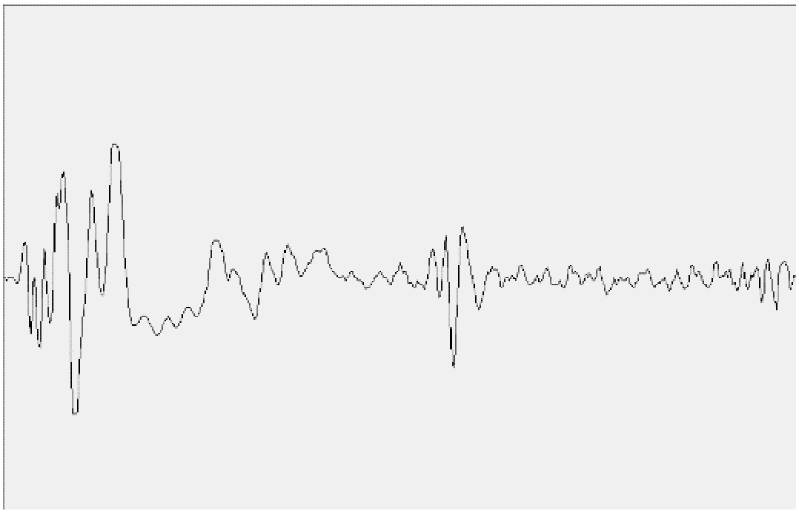

Figure 3 The single-channel data display model

4. Water Content Estimation

4.1. Field Detection and Theoretical Analysis

The width of subgrade is 33.1m, and the total thickness of asphalt pavement is 36cm. The subgrade layer is divided into the upper and lower layer. The upper layer is cement stabilized macadam with a thickness of 23cm. The lower layer is graded crushed stone with a thickness of 25cm. The final thickness of the structure layer reaches 100-110cm.

In actual detection, 450m experimental section was selected for field detection, and the center frequency of antenna was 900MHz. The values of some detection parameters are shown in Table 1. In the post-interpretation, the original image needs to be processed by background removal, filtering and deconvolution, so as to suppress interference waves, highlight effective signals and improve the signal-to-noise ratio [6], [7].

Table 1 Detection parameters

Parameters	Values
Center frequency of antenna/MHz	900
Movement speed/cm s^{-1}	5-10
Samples	512
Superposition coefficient	5
Dielectric constant	5-7

A large number of studies have shown that the existence of water will increase the relative dielectric constant of the medium, and how to establish the relationship between the relative dielectric constant and the water content is the key to determine the water content. To this end, after a lot of fitting and modification, the TOPP formula is regarded as an empirical formula with good approximate effect at present, as shown in Eq.2 [8], [9].

$$\theta_v = 5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon^2{}_r + 4.3\times10^{-6}\varepsilon^3{}_r \quad (2)$$

Where: the left side represents the volumetric water content and it is dimensionless. It is obviously that the formula is a cubic polynomial, in which there is only an unknown relative dielectric constant, and when its value is known, the water content can be calculated. Compared with other complex calculation methods or equations, this sample equation is more effective and easier to estimate the water content of the medium.

4.2. Estimation Results

Using the above methods, a total of 102 actual detection images and 108 drill cores were obtained.

Based on the above analysis, the water content was estimated and measured by TOPP equation and laboratory measurement respectively, and the statistical results were listed in Table 2 (only the statistical data of 10 drill cores are listed for space limitation). It can be seen that for most sample cores, the water content obtained by the above two methods is generally similar, which indicates that the above theoretical analysis and estimation route is feasible and has certain application reference value.

Table 2 Statistical results of water content

NO.	Estimation results(%)	Drilling measurement results(%)
1	6.32	6.19
2	12.87	11.22
3	21.92	20.11
4	18.27	18.11
5	7.21	6.88
6	13.11	11.98
7	5.27	5.48
8	21.49	20.52
9	7.23	7.07
10	16.58	15.62

5. Conclusions

The accumulated water in the road structure layer will directly affect the integrity, stability and even driving safety of the pavement structure. In this paper, based on theoretical analysis and field measurement, the water content of a road structure layer was estimated by using ground penetrating radar detection technology. Conclusions are as follows:

1) Ground penetrating radar has advantages of nondestructive and rapidity in detecting road structural layers, and is suitable for rapid detection of long-distance and large-scale road structural layers.

2) Based on TOPP formula, the method of estimating the water content of road structural layer by using ground penetrating radar detection technology has certain feasibility, which can provide reference for engineering practice, and is a new idea and method, which should be paid attention to in the future.

Acknowledgements

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