Experiment on Artificial Frozen Soil Boundary GPR Detection During Cross-passage Construction in Tunnels

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Abstract

Based on analyzing disadvantage of routine estimate for artificial frozen soil boundary and comparing the dielectric properties differences between artificial frozen and natural soil, experiment on estimating the boundary using Ground Penetrating Radar was discussed for the cross-passage construction of Shanghai East Fuxing road tunnel. For knowing about the amplitude and phase features of GPR reflection of frozen soil boundary, forward modeling was also developed. Despite much EM disturbance the boundary reflection could be obtained from GPR profile by optimizing the data collection mode and selecting appropriate filtering method. By tracing in-phase reflections the boundary could be estimated from GPR profile. Experimental results show that estimated boundary using GPR is consistent with the temperature field distribution deduced from temperature-supervising data. GPR can be used for detecting frozen soil boundary during cross passage construction in tunnel, and also it can make up for the limitation of temperature-supervising method, such as the less temperature-supervising holes and temperature data lost due to sensor damage during construction.

Introduction

In Shanghai soft soil area, the mainly applied and most successful construction technology is the freezing method during cross-passage construction in tunnels. Freezing method is a credible construction technology to deal with the instability watery surface soil, like silt and fluid sand. Freezing boreholes are finished for refrigerating the watery soil around excavated surface. It can consolidate the soft soil, cross-passage excavation can be safety protected by frozen soil (Qiao W.G, 2003). So it is very important to exact distinguish the quality of the freezing construction or the artificial frozen soil boundary. Supervising temperature of frozen soil is a routine method depending on some boreholes, and freezing effect can be estimated by soil temperature filed deduced from temperature data. In fact, only a few supervising holes can be bored and some sensors may be destroyed during construction (Chen X.SH, 1999). It is not enough to distinguish freezing quality only using the finite temperature data. So a non-destructive testing method should be introduced for more exactly and quickly detecting frozen boundary.

Electrical Parameters of Frozen Soil

Soil temperature will change after freezing construction, and the change will result in water migration and soil frozen. Ice may be enrichment or dissipation in different part of soil around the boring holes and different frozen soils will be produced (He P, 1990). Freezing process and dynamic temperature change has a bad effect on electrical property of the soils. Geophysical methods can survey and know about soil geology just using these electrical differences (Koh, G., and S.A, 1999). Freezing construction results in the distinct difference between frozen soil and natural soil, there has the better Geophysical condition for detecting frozen soil boundary. Table 1 shows the difference between frozen and natural soils, such as resistance and relative dielectric constant (Wang W.L, 2003). Obviously, the differences are very much. In all Geophysical survey methods, electromagnetic wave method is most sensitive to the electrical or dielectric differences, such as Ground penetrating radar. GPR is the general term applied to techniques that employ radio waves, typically in the 10 to 5000 MHz frequency ranges, to map structure and features buried in the ground (or in man-made structures). GPR makes use of electromagnetic waves generated into the surface of the object studied by means of antennas moving along the surface. Reflections must be generated when the electromagnetic waves arrive at frozen soil boundary because of the dielectric difference (Gu Zh.W, 1994). There have theory foundation and dielectric difference condition for detecting frozen soil boundary using GPR during cross passage construction in tunnels. And also there have some research on detecting the permafrost table using GPR in cold area (Yu Q.H, Chen G.D, 2002).
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GPR forward simulation and detecting experiment have been finished during freezing construction of the cross passage in Shanghai East Fuxing road tunnel. As a result of very low attenuation in frozen soils, the VHF EM waves can penetrate into long distance, and the attenuation coefficient is only 0.01-1dB/m (Yu Q.H, Chen G.D., 2002; Plewes L A and Hubbard B., 2001). So GPR penetration depth is greater than the distance from frozen soil boundary to detecting surface using 100MHz frequency antennas. Combined with the temperature data, GPR detecting effect and some questions have been discussed.

Table 1: Dielectric parameters difference between the frozen and natural soil

<table>
<thead>
<tr>
<th>Soil</th>
<th>Resistance (Ω·m)</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frozen soil</td>
<td>2000-3000</td>
<td>4-8</td>
</tr>
<tr>
<td>Natural soil</td>
<td>800</td>
<td>10-30</td>
</tr>
</tbody>
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Design of Model and Experiment

Permafrost table GPR detecting results show that the most problem is the strong attenuation of EM waves. Under this detection mode, transmitter and receiver are all put on the ground surface. EM waves firstly generate into the thaw soil and quickly attenuate, so the energy reflected from permafrost table is very weak, and it is difficult to distinguish object reflection and around medium reflection. For overcoming the difficulty, detection mode has been changed during experiment. Transmitter and receiver antennas are directly put on the excavated surface of cross passage like the one shown in Fig.1. Under this detection mode, EM waves firstly generate into frozen soil and arrive at frozen soil boundary, and then receiver will receive the reflected wave from the boundary. There is little EM energy attenuation because the attenuation coefficient is very small in frozen soil. So in GPR profile the reflection of frozen soil boundary will be strong and clear, and easy to identify.

According to the construction schedule, No.3 cross passage is selected for GPR detecting experiment. After excavated surface is enough to operate GPR antennas, we carry out the experimental detection by putting transmitter and receiver on frozen soil surface. Fig.2 shows the survey lines sketch. At both sides of the guide excavated hole of the north tunnel, two survey lines have been finished and antennas move from the top down along survey lines. One survey line has also been finished at the west wall surface of cross passage, and antennas move from north to south tunnel along survey line.

GPR data are collected using pulseEKKO-4 systems manufactured by Sensor & Software Inc. 100MHz frequency antenna has been selected for experimental detection. In GPR profile, reflections are interpreted as a raster image formed by adjacent echoes. Each echoes is displayed as a vertical line extending downward, where the length of the line is proportional to displayed penetration depth. The reflected intensity along the line is denoted by monochrome or color scale.

Experiment Data Analyzing

Forward modeling has been also finished according to model shown in Fig.1 Simulated GPR profiles show that reflection of frozen soil boundary is strong-amplitude and the same phase as direct wave. These characteristics will be the important factors to identify reflection of frozen soil boundary in GPR profile.

In tunnel there exist different EM disturbance sources, such as the power cable, steel lining and support structure. Besides effective object reflection, GPR profile contains much low frequency noises. So it is very difficult to exactly identify reflection of frozen soil boundary and confirm two ways travel time. It is necessary
to remove low frequency noises from GPR profile adopting appropriate filter. Non-linear filter package in Shugunag GPR software has been used to remove noises in experiment (Zhao, Y.H, 2004). Fig.3a shows filtered GPR profile of 3PL survey line. Fig.4a shows filtered GPR profile of 3PR line and Fig.5a shows filtered GPR profile of 3W all line. Compared with original GPR profiles, noises have been removed and reflections of frozen soil boundary have been improved and easy to identify two ways travel time. Certainly, if EM velocity in frozen soil can be exact obtained, the distance from detecting surface to frozen soil boundary would be calculated.

EM velocity mainly depends on the dielectric property of the medium, and can be calculated by formula $v = \frac{0.3}{\sqrt{\varepsilon_r}}$ (m/ns), where $\varepsilon_r$ is relative dielectric constant of the medium. Relative dielectric constant of frozen soil in No.3 cross passage is about 7.0-7.5 by sampling in the site and determining in lab. So EM velocity should be 0.11m/ns in experiment.

In Fig.3a, sequential and strong-amplitude reflections, which are the same phase as direct wave, can be found at two ways travel time range from 72ns to 74ns. These reflections should be reflected from frozen boundary, and distance from detecting surface to boundary changes from 3.8m to 4.0m. Fig.3b shows the interpretation result.

In Fig.4a, sequential and strong-amplitude reflections, which are the same phase as direct wave, can be found
Figure 5: GPR detecting result of 3Wall survey line
(a) filtered GPR profile (b) interpretation result

at two ways travel time range from 74ns to 78ns. These reflections should be reflected from frozen boundary, and distance from detecting surface to boundary changes from 4.1m to 4.2m. Fig.4b shows the interpretation result.

In Fig.5a, sequential and strong-amplitude reflections, which are the same phase as direct wave, can be found at two ways travel time range from 70ns to 74ns. These reflections should be reflected from frozen boundary, and distance from detecting surface to boundary changes from 3.8m to 4.0m. Fig.5b shows the interpretation result.

Figure 6: Designed layout of frozen soil boundary.
(The western side is symmetrical distribution with the Eastern, and the dimension unit: mm)

Fig.6 shows designed frozen soil boundary of No.3 cross passage. The boundary deduced from supervising temperature field is generally consistent with the designed boundary, and freezing effect on the west side of cross passage is better than on the east side. It means that the distance from detecting surface to frozen boundary on the west side is greater than on the east side.

At the position of 3PL survey line, supervising temperature field reveals that the distance from detecting surface to frozen boundary is about 3.9m～4.0m. The difference between GPR interpretation result and supervising temperature result is less than 2.5 percent.

At the position of 3PR survey line, supervising temperature field reveals that the distance from detecting surface to frozen boundary is about 3.1m～4.2m. The difference between GPR interpretation result and supervising temperature result is less than 5 percent.

At the position of 3Wall survey line, supervising temperature field reveals that the average distance from detecting surface to frozen boundary is greater than 3.8m. The difference between GPR interpretation result and temperature supervising result is less than 5 percent.

Obviously, the comparison result satisfies engineers and designers. If it is possible to finish more survey lines or grid lines, frozen boundary of the whole cross passage could be drawn.

Conclusion

Experimental results show that GPR can be used for detecting frozen soil boundary during cross passage construction in tunnels. Despite much EM disturbance the boundary could be obtained from GPR profile by optimizing the data collection mode and selecting appropriate data process method. The difference between GPR interpretation result and temperature-supervising result is only about 5 percent. And also if environmental
disturbance is suppressed, GPR could get more exact result. Combined with supervising temperature method, GPR can make up for the limitation, such as the less temperature-supervising holes and temperature data lost due to sensor damage during construction. In order to introduce GPR into actual engineering application instead of experiment, more research should be developed as follows.

First more effective filter method should be developed for abstracting reflection of the boundary. Second, Forward modeling is good help for knowing about features of EM wave in frozen soil and improving level of GPR profile interpretation. So it is very important to develop GPR forward model of frozen soil.

REFERENCES