RAIL TRACK CONDITION ASSESSMENT USING GROUND PENETRATING RADAR

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Abstract

Ground penetrating radar (GPR) has been increasingly used for monitoring rail track conditions in recent years. GPR can be used to locate interfaces and underground utilities, and evaluate ballast fouling conditions, moisture content and subgrade conditions depending on frequencies of antenna and data processing techniques. In Australia, trial testing on railway sections has been conducted by the railway industry. However, in these trials, testing is only conducted on actual tracks where the relationship between track conditions and GPR response has not yet been established. In this paper, a full scale model rail track designed and constructed at the University of Wollongong is used to investigate factors that influence GPR data quality, such as GPR antenna frequency, the degree and moisture content of ballast fouling and sampling frequency. GPR testing was conducted using ground coupled antennas with different frequencies. Comparisons are made to identify the suitable frequency applicable for the assessment of track condition which will be used subsequently to improve the accuracy of site investigations.

Key words: GPR, rail track, fouling, ballast

1. INTRODUCTION

Ground penetrating radar (GPR) can evaluate rail track substructure condition rapidly and nondestructively \cite{1, 2}. Therefore, it has been widely used to monitor rail track in various countries in the last decade, including UK, Europe, North America, China and etc. In Australia, rail companies, such as Queensland Rail (QR), RailCorp and Australian Rail Track Corporation (ARTC) have conducted series of field GPR testing using different kinds of GPR equipment. Some of the results have been used to aid in determining track maintenance schedules.

The GPR technique utilizes the response of radar signal when it travels in media having different dielectric constants. In different ground media, the propagation velocity of radar signal is different \cite{3}. Strong reflection will be recorded when the GPR signal travels through an interface between materials with different dielectric permittivity, so that the interface can be located \cite{4, 5}. The thickness of each layer can then be calculated based on the propagation velocity and two-way travel time of the radar wave \cite{6}. Absence or change in depth of the interface between ballast and sub-ballast (or capping layer) may indicate that ballast at those locations is fouled \cite{4}. Thickness of clean ballast can be directly calculated based on the recorded radargram if there is a distinct interface between clean and fouled ballast. However, the ballast is sometimes progressively fouled and no interface can be observed on the radargram. Roberts et al. \cite{7} and Al-Qadi et al. \cite{8} introduced a method to evaluate ballast fouling using scattering amplitude of the GPR signal of a 2GHz antenna. They also tried to correlate the strength of the scattering amplitude to the degree of ballast fouling and moisture content.

As there is a relationship between dielectric permittivity and radar signal propagation velocity, dielectric permittivity can be calculated based on the propagation velocity. The propagation velocity can be calculated by the measured two-way travel time of a single antenna and depth of an interface revealed by excavating trenches. In addition, it can be measured by multi-offset antennas without digging trenches \cite{9}. This makes it possible to estimate degree of ballast fouling by comparing
Most of the GPR testing conducted so far was carried out on actual operational railway lines. There are a lot of uncertainties within the actual rail track and it is difficult to calibrate the GPR data with accurate track conditions because only limited number of trenches can be excavated. Variation of degree of fouling is also constricted to the actual track condition. No GPR testing on model track with known conditions is found in the previous literature. In order to investigate factors that influence GPR responses, a full-scale model track with both clean and fouled ballast sections has been built at University of Wollongong. GPR testing using antennas with different frequencies was conducted on the model track. The obtained results are presented and discussed in this paper.

2. THE MODEL TRACK

Fig. 1 shows a schematic diagram of the model track where the units shown are centimetres. The internal dimensions of the box are 4.76m×3.48m×0.79m. The box was constructed with two layers of plywood boards and strengthened with timber bracings. There is a layer of watertight plastic membrane in between the plywood boards so that the subgrade can be fully submerged without any leakage of water.

The track was divided into 9 sub-sections, including 7 fouled and two clean sections. For Sections 1 to 5, the fouling materials were added to the ballast layer by layer during ballast compaction. For Sections 7 and 9, the ballast and fouling materials were firstly mixed using a concrete mixer and then compacted in small layers.

There are two parameters currently used for classifying ballast fouling. One is the Fouling Index $F_I = P_4 + P_{200}$ [10], in which $P_4$ and $P_{200}$ are percentages of ballast particles passing the 4.75 mm sieve and 0.075 mm sieve respectively. Another is the Percentage Void Contamination (PVC), which measures the percentage of voids of ballast occupied by fouling material [11]. $F_I$ does not consider the influence of specific gravity of fouling material, while PVC does not take the voids between fouling particles into account. Therefore the degree of fouling here is categorized using a parameter named Relative Ballast Fouling Ratio ($R_{b-f}$) developed by Indraratna and Su [12] which is defined as:

$$R_{b-f} = \frac{M_f \times \frac{G_{s-f}}{G_{s-b}}}{M_b} \times 100\%$$ (1)

where, $M_f$ and $M_b$ are mass and specific gravities of fouling materials and ballast, respectively.

3. GPR DATA ACQUISITION

Data were acquired in April 2009 using an IDS Safe Rail System with three 400 MHz and one 2 GHz ground coupled antennas. A Doppler radar position encoder is used to measure the traveling distance of the antennas. Fig. 2 shows...
the control unit and 400 MHz antennas mounted to a railway trolley. Fig. 3 shows the travelling lines along which the inspection was conducted, including one line located along the center of the track and other two lines located at the end of the sleepers.

Samples per scan: 512;
Antenna orientation: in $y$ direction for the 400 MHz antenna and both $y$ and $x$ directions for the 2 GHz antenna.
Data was firstly collected under dry conditions using both of the 400 MHz and 2 GHz antennas with different sampling intervals. To simulate the wet track, water was then sprinkled on the ballast surface and the excessive water drained away via the drainage pipes on the capping layer surface. 24 hours after the initial watering.

![Fig. 2 Set-up for data acquisition using the IDS GPR system](image)

![Fig. 3 Travelling lines of GPR antenna](image)
of the ballast, data was collected again under wet conditions. Fig. 4 shows a photo of watering the ballast.

**Fig. 4 Watering the track**

4. DATA PROCESSING

Raw data was processed using Reflex 2D Quick to enhance signal-noise ratio and highlight interfaces and radargram textures. The processing includes band pass filtering, Direct Current (DC) and background removal and gain control. Only very fundamental filters were applied to the raw data to avoid introducing artificial textures into the radargram.

A comparison between raw and processed data obtained by one of the 400 MHz antennas under dry condition is presented in Fig. 5. The depth in the radargrams was calculated based on an estimated speed of $1.1 \times 10^8$ m/s. For the raw data, an interface can be observed at the time of about 15 nanoseconds (ns) but there is no useful information that can be obtained close to the ballast surface because of noise. After the above mentioned filters have been applied, an obviously improvement of the signal/noise ratio can be observed. Some hyperbolae are shown on the radargram close to the ballast surface showing the location of the sleepers. Changes in two-way travel time of the radar signal traveling in different sections are also shown on the radargram.

5. DISCUSSION ON PROCESSED DATA

5.1 Effects of Radar Detectable Geotextile

Radar detectable geotextile is composed of a two-layer non-woven geotextile covering an aluminum foil sheet. GPR signal is strongly reflected by metal foil so that the radar detectable geotextile is often used to highlight substructure interfaces. In the model track, radar detectable geotextile was embedded under the ballast along Line 1 (Fig. 3). Fig. 6 shows the GPR images obtained along lines with and without radar detectable geotextile under dry condition. A clear interface between the ballast and capping layer is shown on the GPR image obtained along Line 1. On the GPR image obtained along a line without radar detectable geotextile, no interface can be
located under dry condition. This indicates that the radar detectable geotextile is very useful in highlighting interfaces.

**5.2 Influence of Frequency**

Fig. 7 shows GPR images obtained using the 400 MHz and 2 GHz antennas along Line 2 respectively. In general, the image of the 2 GHz antenna is much clearer than that of the 400 MHz antenna. A clear and continuous interface at about 11 ns is shown on the image of the 2 GHz antenna, which is the interface between the ballast and the capping layer. The same interface cannot be located on the GPR image of 400 MHz antenna. The range influenced by sleepers of the two antennas is almost the same in both horizontal (about 0.6 metre) and vertical (about 5 ns) directions. The depth of
penetration of the 2 GHz antenna is as good as the 400 MHz one. This indicates that the overall quality of the data obtained by the 2 GHz antenna is better than that of the 400 MHz. It is noted that the sleeper spacing of model track is larger than that of the common track thereby yielding a better GPR response. Influence of sleepers with standard spacing will be studied in the future field model testing.

5.3 Influence of Moisture Content

The dielectric permittivity of water is 81 while that of dry clean ballast is only about 3 [13]. After water flowed through the ballast, it will be retained in fouled sections of ballast, the higher the degree of fouling is, the more the water will be retained. The moisture content largely increases the dielectric permittivity of fouled ballast. As only limited water will be retained in clean ballast, the increase in dielectric permittivity of clean ballast is not significant. As expected, the increase in difference between dielectric permittivity of clean and fouled ballast will elucidate the interfaces. Fig. 8 shows the GPR images obtained by 400 MHz antenna along Line 1 under dry and wet conditions, respectively. There is no notable interface between clean and fouled ballast on the GPR image obtained under dry condition. However, an interface between clean and fouled ballast can be observed on the GPR image obtained under wet condition. The GPR images of the 2 GHz antenna showed similar effects. This indicates that high moisture content is favorable for GPR to locate fouled ballast. However, wet ballast condition is unfavorable for GPR inspection because the high dielectric permittivity can substantially reduce the depth of penetration of GPR signal.

5.4 Influence of Sampling Interval

Sampling interval was varied from 0.012 m to 0.06 m during collecting the GPR data to study the influence of sampling frequencies on the quality of the GPR data. Fig. 8 shows the GPR images obtained by 400 MHz antenna along Line 1 at sampling interval of 0.012 m, 0.036 m and 0.06 m, respectively. It can be observed that the two GPR images are almost the same except that there are a little more textures on the image with sampling interval of 0.012 m. This indicates that the sampling interval for a given range has a slight influence on the quality of the GPR data.

CONCLUSIONS

GPR testing conducted on a full scale model track at the University of Wollongong is presented in this paper and the processed GPR data is presented and discussed. Factors that will influence the quality of GPR data, such as presence of radar detectable geotextile, GPR antenna frequency, moisture content and sampling interval are investigated. The following conclusions can be drawn based on analysis of the GPR data:

- The radar detectable geotextile is very useful in highlighting interfaces;
- The overall quality of the data obtained by the 2 GHz antenna is better than that of the 400 MHz one.
c) High moisture content is favorable for GPR to locate fouled ballast.

d) The sampling interval almost has no influence on the quality of the GPR data when it changes in a small range.

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Outline of the presentation

Outline

- GPR application on track assessment
- A laboratory model track
- GPR data acquisition and processing
- Discussion on processed data
- Conclusions
GPR application on track assessment

➢ Theory background of GPR

\[ v = \frac{2\sqrt{h^2 + d^2}}{4t} \]

\[ v = \frac{c}{\sqrt{\varepsilon_r}} \]

\( v \) — wave-propagation velocity;

\( c \) — speed of light in a vacuum

\( h \) — layer thickness;

\( \varepsilon_r \) — two-way travel time.

\( d \) — offset between transmitter and receiver;

\( t \) — two-way travel time.
GPR application on track assessment

GPR applications

😊 Advantages of GPR

- Non-destructive and rapid.

😊 Locating underground interface

- By strong reflections from the interface.

😊 Detecting ballast fouling

- By Absence or change in depth of the ballast-capping interface;
- By attenuation of GPR signal;
- By comparing the relative dielectric permittivity;
- By comparing radargram textures

2009-10-30
A laboratory model track

Section plans

Coal: $R_{b-f} = 10\%$

Coal: $R_{b-f} = 25\%$

Ballast breakdown: $R_{b-f} = 25\%$

Clay: $R_{b-f} = 25\%$

Clay: $R_{b-f} = 10\%$

Clean Ballast

Clay: $R_{b-f} = 50\%$

Coal: $R_{b-f} = 50\%$

Dimensions:

- 15.15
- 60
- 60
- 60
- 60
- 30
- 40
- 60
- 50
- 56
- 476

Date: 2009-10-30
Parameters for classifying ballast fouling

- **Parameters for classifying ballast fouling**

\[
FI = P_4 + P_{200}
\]

- \( P_4 \) — percentage of ballast particles passing 4.75 mm sieve;
- \( P_{200} \) — percentage of ballast particles passing 0.075 mm sieve;

\[
PVC = \frac{V_2}{V_1} \times 100\%
\]

- \( V_1 \) — volume of ballast voids;
- \( V_2 \) — total volume of fouling material;

\[
R_{b-f} = \frac{M_f \times G_{s-b}}{G_{s-f} \times M_b} \times 100\%
\]

- \( R_{b-f} \) — Relative ballast fouling ratio;
- \( M_f \) — mass of fouling material;
- \( M_b \) — mass of ballast;
- \( G_{s-f} \) — specific gravity of fouling material;
- \( G_{s-b} \) — specific gravity of fouling material.
Data acquisition

GPR data acquisition and processing
GPR data acquisition and processing

Data acquisition

Set-up for data acquisition using the IDS GPR system
GPR data acquisition and processing

Data processing

Comparison between raw (top) and processed (bottom) GPR data (dry)
Discussion on processed data

- Effects of radar detectable geotextile

GPR Image of 400 MHz antenna under dry condition

- Cross line 1
- Cross line 2
- Cross line 3

2009-10-30
Discussion on processed data

Effects of radar detectable geotextile

GPR Image of 400 MHz antenna under wet condition

Cross line 1

Cross line 2

Cross line 3

2009-10-30
GPR Image of 2.0 GHz antenna under dry condition

- Cross line 1
- Cross line 2
- Cross line 3
GPR Image of 2.0 GHz antenna under wet condition

Cross line 1

Cross line 2

Cross line 3
Discussion on processed data

Effects of frequency

GPR images obtained along Line 2 under dry condition by 400 MHz (top) and 2 GHz (bottom) antennas respectively
Influence of moisture content

Comparison between GPR Images of 400 MHz antenna under dry (top) and wet (bottom) conditions (Line 1)
Discussion on processed data

- Influence of moisture content

Comparison between GPR Images of 400 MHz antenna under dry (top) and wet (bottom) conditions (Line 3)
Discussion on processed data

- Influence of moisture content

Comparison between GPR Images of 2.0 GHz antenna under dry (top) and wet (bottom) conditions (Line 2)

2009-10-30
Discussion on processed data

- Influence of moisture content

Comparison between GPR Images of 2.0 GHz antenna under dry (left) and wet (right) conditions (Line 3)
GPR images obtained by 400 MHz antenna at sampling interval of 0.012 m (top), 0.036 m (mid) and 0.06 m (bottom) respectively
Conclusions

- The radar detectable geotextile is very useful in highlighting interfaces;
- The overall quality of the data obtained by the 2 GHz antenna is better than that of the 400 MHz one;
- High moisture content is favorable for GPR to locate fouled ballast;
- The sampling interval almost has no influence on the quality of the GPR data when it changes in a small range.
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