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Non-destructive assessment of rail track condition using ground penetrating radar

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Abstract

Ground penetrating radar (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 the 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 the GPR data quality, such as the 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.

1 INTRODUCTION

Ground penetrating radar (GPR) can evaluate rail track substructure condition rapidly and nondestructively (Al-Nuaimy et al. 2004, Eriksen et al. 2006). Therefore, it has been widely used to monitor rail track in various countries in the last decade, including the UK, Europe, North America and China. 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.

In different ground media, the propagation velocity of the GPR signal is different (Daniels 2004). 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 (Jack & Jackson 1999, Sussmann et al. 2003). The thickness of each layer can then be calculated based on the propagation velocity and two-way travel time of the GPR signal (Hugenschmidt 2000). Absence or change in depth of the interface between ballast and capping layer may indicate that ballast at those locations is fouled. Thickness of clean ballast can be directly calculated based on the recorded radargram if there is a distinct interface between clean and fouled ballast. If the ballast is progressively fouled and no interface can be observed on the radargram, ballast fouling can be evaluated using scattering amplitude of the GPR signal of high frequency antennae (Roberts et al. 2006, Al-Qadi et al. 2008).

Relative dielectric permittivity can be calculated based on the propagation velocity of the GPR signal. The propagation velocity can be obtained from 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 (Keogh et al. 2006). This makes it possible to estimate degree of ballast fouling by comparing the dielectric constants.

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. GPR testing on model track with known conditions is very limited in previous literature. In order to investigate factors that influence the 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

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

The track is formed by a subgrade layer of clayey sand, a capping layer of roadbase material and a ballast layer. Saturation pipes were placed at the bottom of
the box and drainage pipes were placed on the surface of the capping layer. 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 premixed 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 \( FI = P_4 + P_{200} \) (Selig & Waters 1994), 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 (Feldman & Nissen 2002). \( FI \) 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 \( (R_{bf}) \) developed by Indraratna et al. (2011) which is defined as:

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

where, \( M_f \) and \( M_b \), and \( G_{c-f} \) and \( G_{c-b} \) are mass and specific gravities of fouling materials and ballast, respectively.

3 GPR DATA ACQUISITION

Data were acquired using an IDS Safe Rail System with three 400 MHz and one 2 GHz ground coupled antennae. A Doppler radar position encoder is used to measure the traveling distance of the antennae. Figure 2 shows the control unit and 400 MHz antennae mounted to a railway trolley. Figure 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.

The acquisition parameters are as follows:

Acquisition speed: typical walking speed (about 1.5 m/s);

Horizontal sampling interval: 0.012 m to 0.06 m;

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 (Fig. 4). 24 hours after the initial watering of the ballast, data was collected again under wet conditions.

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 antennae under dry condition is presented in Figure 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 obvious 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 aluminium 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). Figure 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
Figure 7 shows the 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 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 m) 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. 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. Figure 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. Figure 9 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.

6 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 the GPR data, such as presence of radar detectable geotextile, the GPR antenna frequency, moisture content and sampling interval are investigated. The following conclusions can be drawn based on analysis of the GPR data:
(a) The radar detectable geotextile is very useful in highlighting interfaces;
(b) 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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