High Speed Railway Ballast Characterisation Using Ground Penetrating Radar

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Summary
This paper demonstrates how high speed (80 km/h) GPR is being used operationally in Australia to classify ballast and drainage conditions of actively used railway tracks. By providing this information on an ongoing basis, proactive rather than reactive track maintenance is possible by railway maintenance personnel. GPR scanning has been implemented to classify the operational parameters used by track maintenance personnel, such as:

- Requirement for maintenance or replacement of ballast
- Clay content of ballast
- Ballast volumes
- Optimal setup configuration for ballast cleaning machines to remediate specific track.

The paper also shows how GPR and maintenance records can be combined to enable strategies for optimizing maintenance programmes and to qualitatively assess ballast degradation rates.

INTRODUCTION
Mining operations throughout Australia take advantage of extensive rail networks to transport an ever increasing amount of material from mines to ports. Due to the overseas demand for Australian resources, rail networks in Australia run at near capacity, every day of the year. This high axle loading combined with loads that are uncovered can cause rapid track degradation through formation failure and extensive fouling rates.

Rapid track degradation and near capacity track usage means that minimal time is available to maintain track. It is therefore vital that maintenance operations are run as efficiently and effectively as possible. High speed GPR can be used to rapidly classify track condition without interrupting normal freight operations [3, 5]. This ensures that degraded track is prioritised for maintenance and that resources are not wasted repairing track already in good condition. Using GPR also enables maintenance personnel to be more proactive rather than reactive with their maintenance operations by providing them with the tools they need to make informed decisions to plan maintenance schedules and budgeting. Use of GPR for ongoing monitoring of track condition over time enables qualitative assessments of track degradation rates to be made so that track can be remediated before costly speed restrictions are imposed.

Track substructure plays a vital role in providing shock absorption to rolling stock. The three main components of track substructure are ballast, subballast and subgrade [6]. The formation is made up of the sub-ballast, subgrade and all other layers of fill. The ballast is the top structural layer that holds the track in place and reduces stress transmitted to the sub-ballast and subgrade [6]. The sub-ballast is the second structural layer that helps the ballast reduce the stress, maintains separation
between ballast and subgrade, and plays an important part in track drainage [7]. These two components rest on subgrade (Figure 1).

Figure 1 Diagram of track substructure components.

Ballast fouling is the process where particles from a number of sources infiltrate void spaces between ballast particles including where ballast particles break into smaller particles [6]. Coal fouling is the process where windblown coal dust and particles are deposited into the void spaces between ballast particles and form the predominant type of fouling. Coal fouling quantification tests carried out on the Central Queensland Coal Network have concluded that coal fouling accounts for 70-95% of total fouling [2].

Clay fouling occurs when fine-grained material enters the ballast from the subgrade by the action of repeated loads in a process called pumping [4]. Both of these types of fouling occur in Australia and inhibit the main functions of ballast which are to distribute the load from the sleepers, to damp dynamic loads and to provide lateral resistance and drainage [4].

This paper presents the results of a body of work to determine how GPR can be used to provide operationally important information to rail track maintenance staff. It is envisaged that continuous maps derived from the GPR would be used by maintenance managers to make strategic decisions when planning quarterly and yearly operations and by “on the ground” maintenance personnel to plan daily operations. To do this, the following operationally important parameters were classified:

•Ballast depth\(^1\) (one measurement along track centreline and one either side of this along each sleeper edge)

•Ballast volumes\(^2\) calculated for every 1m, 50m and 1km segment

•Derived cutter depth: This is the depth to which the ballast should be undercut\(^3\) to remove the optimum thickness of fouled ballast and replace with clean ballast without causing damage to the underlying formation. This information can be used to provide the optimal setup configuration of the undercutter for remediating specific track.

•Remediation requirement: Whether the ballast needs replacing, based on the level of total fouling from clay and coal and ballast breakdown.

•Screenability\(^4\): The ability of the ballast cleaning machine to screen (clean) the ballast and replace it to the track. This parameter is derived based on the amount of clay fouling the ballast.

•Drainage condition

•Ballast pockets – a depression that is formed beneath the ballast layer by penetration of ballast particles into the subgrade and that tends to collect moisture [1]

A final objective of this work was to show that comparison of these parameters with maintenance records could be used to provide ballast degradation rates for specific track sections.

1. EQUIPMENT SETUP AND ACQUISITION

The system used for this work is the IDS SafeRailSystem, which comprises three multiplexed 400MHz GPR antennae with control unit and integrated video camera. Accurate positioning of the GPR data is achieved using a combined approach of a decimetre accuracy differential GPS and Doppler encoder. The Doppler encoder alleviates positioning problems encountered encountered.

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\(^1\) Minimum ballast depths and volumes are reported on in areas of clay fouling or lime injection

\(^2\) To obtain these values assumptions are made relating to the surface and base profiles of the ballast

\(^3\) Undercutting is the process of ballast cleaning undertaken by a ballast cleaning machine. This machine lifts the track and removes ballast material from underneath the sleepers, replacing it with clean ballast.

\(^4\) Some ballast cleaning machines have the ability to screen (clean) the ballast and replace it to the track. Only ballast with low clay content is screenable.
through tunnels and cuttings if GPS signal is lost.

The antennae acquire data simultaneously at three offsets with one antenna positioned over the track centreline with the remaining two approximately over the edge of the sleepers. Each trace and photograph captured from the video camera is GPS stamped with a trace recording taken every few cm. This system has collected GPR data from over 5000km of track throughout Australia at speeds of up to 100km/hr.

The system has been mounted onto locomotives, ballast tamping machines (Figure 2), track recording cars and hy-rail vehicles. In Australia the hy-rail vehicle provides good flexibility in manoeuvring on and off track particularly near mines and ports where trains can spend several hours loading and unloading material.

![Figure 2 – IDS SafeRailSystem setup showing three 400 MHz antennae and Doppler encoder.](image)

2. PRESENTATION OF OPERATIONALLY IMPORTANT PARAMETERS

Instead of scientific terminology and confusing radargrams, some clients simply want to know whether GPR will give them the information they require to enable them to make informed tactical and strategic decisions to maintain their assets more efficiently. The focus of this work was to address this by converting radar parameters into the operationally important parameters traditionally used to assess track quality.

To do this, it was necessary to gain a detailed understanding of maintenance operations and then present information in a way that was useful and could be easily used by maintenance managers, engineers and field operators of the undercutter. Figure 3 is an example of a strategic planning map that has been customized to meet these specifications. This strategic planning map indicates from the top down:

- derived cutter depth and ballast volumes;
- screenability index where blue indicates screenable and orange indicates unscreenable ballast;
- ballast depths from antennas 1 to 3;
- remediation requirement index where red indicates that ballast requires remediation and green indicates that ballast does not require remediation;
- drainage index where drainage is toward darker shades of grey;
- a plan view of track position; and
- Trench positions marked by vertical drill holes.
Information from the plots as well as trench information can then be overlain or added as .kml files into Google Earth (Figure 4). This figure shows a drainage overlay with floating display of remediation requirement. For the drainage display, blue indicates the deepest ballast and red the shallowest ballast. For the remediation display, green indicates ballast in good condition and red indicates ballast in poor condition. In this way features such as ballast pockets and remediation requirement can be related to geographic features.

3. IMPORTANCE OF DIFFERENTIATING BETWEEN CLAY AND COAL FOULING

Extraction of the complete operational parameter set would not be possible without the ability to differentiate between clay and coal fouling. The level of clay fouling is the most important factor (along with associated water absorption) affecting the screenability of the ballast and is also one of the major limiting factors (along with ballast volume) affecting undercutter production rates [8]. Coal fouled ballast is typically screenable and mildly inhibits undercutter production rates [8]. If the level of clay fouling is known, the screenability of the ballast can be determined and operationally important information derived. Such information typically includes:

• the volume of non-screenable / screenable ballast
• the volume of new ballast required to be added to track; and
• daily production rates through screenable and non-screenable areas.
Clay fouling typically emanates from below the base of the ballast\(^5\) and is caused by clay pumping upwards from a soft formation. This process is exacerbated by poor drainage. Our studies have found that the GPR signatures of clay fouled ballast generally exhibit a more undulating interface between clean and fouled ballast that is closer to the base of the sleeper than for recently undercut ballast. See Figure 7 (clay fouling example) and Figure 9 (recently undercut example) later in this paper.

It has been found that in all areas tested to date in Australia, clays within the ballast attenuate the GPR signal and no layer boundaries beneath the clean/clay fouled ballast interface can be seen unless the clays are completely dry. Trenching in clay fouled areas has typically shown the base of the ballast to be masked by clay fouling within the ballast profile (Figure 5). In this example the trench showed that the actual base of ballast was coincident with the boundary at the top of the green in the core, however the GPR estimated the base of ballast to be at the base of the red in the core. This meant that the actual base of the ballast was being masked by the clay and could not be seen by the GPR. For this reason, minimum ballast depths are reported on in clay fouled areas. The inset within the figure also shows a photograph of the trench at this location.

GPR signatures of coal fouled ballast is characterised by high amplitude reflections from within the ballast and low amplitude reflections from the base of the ballast. Increasing the level of coal fouling increases the amplitude of reflections within the ballast and decreases the amplitude of reflections from the base of the ballast. This is due to the fact that coal dust and particles foul the ballast and accumulate and retain moisture. The presence of moisture increases the dielectric contrast within the ballast causing increased scattering and reduced transmission of the GPR wave. Figure 6 shows an example of recently undercut ballast showing low amplitude reflections within the ballast and high amplitude reflections at the base of the ballast. Figure 7 shows an example of highly coal fouled ballast showing high amplitude reflections within the ballast and low amplitude reflections at the base of the ballast.

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\(^5\) Ballast can also breakdown to fine clays to cause clay fouling and can be difficult to distinguish from formation pumping.
Drainage index where drainage is toward darker shades of grey.

The plot can be divided into 3 track sections which are labelled Section A, B and C and are described in more detail below:

4.1 Section A
This section of the track was undercut more than 5 years prior to the GPR survey date.

Based on the GPR data (Figure 9) the majority of the track is interpreted to have a fouled upper layer and clay fouled lower layer. The upper fouled layer is interpreted as coal fouling or breakdown of the upper ballast and the interface between this upper layer and the lower clay fouled layer is highly undulating. The clay fouled lower layer is masking the identification of the actual ballast base for a significant portion of this track.

Figure 8 – Strategic planning map.

The trench photos (Figure 10) suggest that this section of track contains moderate moisture and high clay content in the lower layer with a generally coal fouled upper layer resulting in predominantly unscreenable material in need of remediation. The trenches also indicated that clay was present up to or near the base of the sleeper for 4 of the 5 trenches excavated for this section of track (Section A). This is consistent with the GPR interpretation as outlined on the strategic planning map where all of Section A is in need of remediation with the majority of this section unscreenable.

Drainage appears to be mostly toward the outside track indicating that the fouled lower layer is deepest along the outside section of the track. The strategic planning map highlights the greater need for remediation required for this section of track compared to Sections B and C which were undercut more recently.
4.2 Section B
This section of track was undercut only 6 months prior to the GPR survey date. The strategic planning map and the GPR data (Figure 11) in this section is quite different to Section A in that this undercut section shows a reflector that is relatively flat and consistent throughout the entire section. This layer is interpreted to be the depth to which the track was previously undercut and shows limited clay ingress. This section of track is generally in good condition with a clean upper layer with little to no fouling and a very consistent flat base. This interpretation is consistent with trenches in this section, one of which is shown in Figure 12.

4.3 Section C
This section of track was undercut 2 years prior to the GPR survey date. The inferred interface on the strategic planning map corresponding to the top of clay fouled ballast is generally closer to the track level and more undulating compared to ballast undercut 6 months before the GPR survey date. This highlights evidence of rapid track degradation over time and reinforces the need for ongoing monitoring. Example data from this location is shown in Figure 13 and shows a more undulating ballast base which is higher in the profile than the more recently undercut Section B. An example trench from this location is shown in Figure 14.
5. CONCLUSIONS/REMARKS

This paper shows how GPR data collected at high speed on Australian railway track can be converted into the operational parameters required by maintenance staff to improve the efficiency of operations. It shows that these parameters can be presented in formats that are useful on a tactical and strategic level through the use of strategic planning maps and Google Earth output. It outlines the use of subtle differences in the GPR signal to differentiate between different types of ballast fouling and the importance of this in determining the operationally important parameters. It also shows how maintenance records can be combined with GPR surveys to indicate relative ballast degradation rates. Whilst this paper is focussed on coal networks, a similar philosophy has also been successfully applied to iron ore networks in Australia.

GPR is an excellent tool for assessing ballast condition but it is important to combine this information with other records such as track geometry, linescan camera imagery and ultrasonics, to provide a better picture of above and below rail health. Combining above and below rail measurements improves maintenance planning and allows for more proactive scheduling of track maintenance and optimal allocation of machines, manpower and resources.

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REFERENCES


