PLANNING BALLAST CLEANING USING BALLAST FOULING LEVELS DETERMINED WITH GROUND-PENETRATING RADAR

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SUMMARY

To maintain adequate track top and line, ballast needs to perform all required functions, including spreading loads from rail traffic to the formation and rail drainage. If ballast voids become contaminated ( fouled), the performance of these functions is reduced.

An effective method of removing fouling material is ballast cleaning, however the cost to purchase and operate ballast cleaning machines is high, and they require track possessions that occupy train paths. Optimising ballast cleaning locations and timing is critical for maximising long term performance and availability of rail networks.

QR National has used Percentage Void Contamination (PVC) values determined from laboratory testing to measure ballast fouling levels for several years. However, PVC sampling and testing is slow, costly and only provides PVC values at actual sample locations (typically at 500m or 1km intervals). PVC sampling also requires track possessions that reduce network availability for rail traffic, and involves personnel performing activities on track where safety risks need to be well managed.

QR National has recently developed a new method of developing detailed ballast cleaning plans for rail systems, using PVC values determined from ground-penetrating radar (GPR) testing. This new method is faster (from a data capture viewpoint), cheaper and safer than the PVC sampling and testing method, and provides substantially more ballast fouling level information. This paper describes this new method, including calibration of GPR PVC values from laboratory PVC values.

INTRODUCTION

QR National owns and operates the Central Queensland Coal Network (CQCN), a heavy haul rail network consisting of the following four coal systems:

- Moura System: ports at Gladstone
- Blackwater System: ports at Gladstone,
- Goonyella System: ports: Hay Point and Dalrymple Bay;
- Newlands System (including GAP project): port: Abbot Point.

The total track length of this network is approximately 2500km, and the total net tonnage of coal transported on these four systems is currently approximately 160Mnt/a.

In order to maximise availability of this rail network, the performance of all track components needs to be optimised. Along with rail and sleepers, ballast is an integral track component, and poor ballast performance will reduce network availability.

BALLAST FOULING

Ballast performs several functions, including adequately distributing rail traffic loads from the base of sleepers to the formation, and providing drainage from the track structure. New ballast contains approximately 40% voids, however if these voids become filled (or fouled), ballast performance is reduced, resulting in reduction in load-spreading and drainage capability.

1. Ballast fouling materials

Ballast fouling materials on the CQCN include:

- coal fines (predominant type of fouling material),
- degraded ballast particles,
- formation material pumped into ballast layer by rail traffic.
2. Inspection trenches

Some examples of track cross sections at inspection trenches are shown in Figures 1 and 2. Figure 1 illustrates a track cross section with ballast highly fouled with coal fines (virtually all ballast voids filled with coal fines).

![Ballast highly fouled with coal](image1)

*Figure 1: Ballast highly fouled with coal*

Figure 2 shows a track cross section with the following ballast sub-layers, on an intact formation:

- upper sub-layer: clean ballast,
- lower sub-layer: ballast highly fouled with a mixture of degraded ballast and some coal fines.

![Lower ballast sub-layer highly fouled with a mixture of degraded ballast and some coal fines](image2)

*Figure 2: Lower ballast sub-layer highly fouled with a mixture of degraded ballast and some coal fines*

3. Impacts of fouled ballast

Impacts from ballast fouling can include track "top and line" irregularities and creation of "mudholes". Mudholes are concentrations of fine material from within the ballast layer, with the source of this fine material on the CQCN generally being either (or a mixture of both):

- degraded ballast due to high rail traffic levels and high axle loads,
- coal fines.

An example of a mudhole is shown in Figure 3.

![Mud-hole](image3)

*Figure 3: Mud-hole*

Note that a "clayhole" is similar in appearance to a mudhole, however the source of ballast fouling material at a clayhole is material...
migrating up into the ballast layer from the formation.

Speed restrictions may need to be applied at
mudholes and at track sections with poor top
and line, so that safe operation of rail traffic
can continue, until repair works can be
performed. However, speed restrictions
result in increased train running times across
the network.

4. Ballast fouling sources and mitigation
methods

Preventing coal fines from fouling ballast is of
prime importance to QR National. The main
sources of these coal fines, and mitigation
measures, are included in Table 1.

<table>
<thead>
<tr>
<th>COAL FOULING SOURCE</th>
<th>TYPICAL FOULING LOCATION</th>
<th>MITIGATION METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal fines falling from or blown off top of wagons</td>
<td>Close to loading points, open areas with cross winds and at turnouts</td>
<td>Load wagons to a “garden bed” profile and apply veneering compound to the exposed coal surface</td>
</tr>
<tr>
<td>Coal fines “hung up” on wagon components during unloading</td>
<td>Downstream of port unloaders</td>
<td>Reduce wagon “ploughing” during unloading</td>
</tr>
</tbody>
</table>

These mitigation methods are gradually being
implemented throughout the CCQN, however a
significant ballast fouling legacy currently
exists in the CCQN.

Ballast fouling on the CCQN is also minimised by
use of ballast meeting a specification that
includes extensive strength and durability test
requirements, and an extensive formation
design, evaluation, repair and improvement
process.

BALLAST CLEANING

1. Ballast cleaning machine

The most effective method of removing
fouling material from ballast is to use a ballast
cleaning machine (BCM). Ballast cleaning
machines operate by removing fouled ballast
from track, screening fouling material from
ballast particles, recycling screened ballast
back into track and dumping fouling material.
If fouled ballast includes wet clay, this ballast
is not screenable and needs to be dumped.
New ballast may also be required to
supplement screened ballast (or to fully
replace fouled ballast that is not able to be
screened). A QR National BCM is shown in
Figure 4.

Planning ballast cleaning works using ballast fouling
levels determined with ground-penetrating radar

2. Planning ballast cleaning machine (BCM)

Ballast cleaning machines are expensive to
purchase and operate, and require full track
possessions for operations which reduce
network availability. Thorough planning of
ballast cleaning works is essential.

Planning ballast cleaning includes the
following two aspects:

- high level: selection of ballast cleaning
  locations,
- detailed level: assessment of ballast
  screenability.

MEASUREMENT OF BALLAST FOULING LEVELS

1. Fouling Index

Ballast fouling levels have generally been
measured using the mass-based Fouling
Index (FI) throughout the world:

\[ FI = \% \text{ passing } 4.75mm \text{ sieve} + \%
\text{ passing } 0.075mm \text{ sieve} \]  

[Equation 1]  
[Reference 1]

2. Percentage Void Contamination (PVC)

Fouling Index is suitable for measuring ballast
fouling levels if fouling materials, such as
degraded ballast particles or formation
material, have similar densities to ballast
particles. However, this method is inaccurate
if fouling materials have different densities to
ballast particles. The density of coal fines, the
predominant QR National fouling material, is
approximately 0.90 \text{m}^3. This is significantly
different from the density of ballast particles of
approximately 2.70 \text{m}^3. Based on this density
variation, QR National developed the volume-
based Percentage Void Contamination (PVC)
method [Reference 2] approximately 10 years
ago. PVC testing is performed on samples of
ballast obtained between the top of sleepers
and the base of the ballast layer (including crib ballast). PVC is calculated as follows:

$$\text{PVC} (\%) = \frac{V_2}{V_1} \text{[Equation 2]}$$

where: $V_2$ = volume of fines, $V_1$ = volume of voids in ballast.

Coal fines generally migrate to the base of the ballast layer from washing by rain or vibration from rail traffic. Accumulation of these coal fines at the base of the ballast layer result in a reduction in the depth of clean ballast below the base of sleepers. Once the depth of clean ballast below the base of sleepers is reduced to less than approximately 100mm, track top and line deterioration can occur more rapidly. Based on the voids content of clean ballast of approximately 40% (available storage volume for fouling material within total volume of compacted ballast), this clean ballast depth of 100mm is equivalent to a PVC value of approximately 30% (ballast cleaning intervention level), as shown in Figure 5.

**Figure 5: Depth of fouling material in ballast layer at a PVC value of approximately 30%**

An advantage of the PVC method is that ballast fouling rates can be easily determined. For the CCQN, coal fines from rail traffic can be correlated to changes in PVC values, from multiple PVC samples obtained at different times from the same sample locations. For fouling caused only by ballast degradation from rail traffic, the same method can be applied, as ballast degradation can be correlated with rail traffic levels.

QR National have been performing PVC tests on ballast samples obtained from test pits from the track centreline typically at 500m or 1km intervals. An assessment of ballast screenability has also been obtained from a visual assessment of these PVC ballast samples. PVC test results are accurate for ballast samples, however PVC values could vary considerably between PVC sample locations. Also, only approximately 8 PVC samples can be obtained and tested per closure day (closure days only approximately once per month per coal system) resulting in only approximately 206 PVC samples tested per annum.

As only a small number of PVC samples have been obtained to date, track sections with fouled ballast throughout the CCQN have primarily been identified from visual assessments by maintenance personnel, with these locations then being verified with PVC sampling.

**MEASURING BALLAST FOULING LEVELS WITH GPR**

1. **Calibration**

QR National has been measuring ballast fouling levels with GPR on a small scale since approximately 2007. However, these ballast fouling levels have been based on a visual classification system. In 2010, QR National engaged ZeticaRail to capture GPR data from over approximately 700km of track on the Goonvella System, including measurement of ballast fouling levels. ZeticaRail had previously measured ballast fouling levels from GPR data in terms of Fouling Index, however had not reported this in terms of PVC values. Based on the extensive historical PVC data that QR National had developed, familiarity of the PVC method within QR National and a desire to continue measuring ballast fouling levels in terms of PVC values, a calibration between GPR signals and PVC values was performed.

Initially this calibration involved identifying locations with a range of fouling levels in GPR data from track sections, then performing additional targeted GPR testing followed immediately by PVC sampling. However, after obtaining approximately 30 PVC samples, an adequate distribution of PVC values had not been achieved. In order to achieve this distribution, a track panel incorporating the required distribution of PVC values was constructed. This track panel included 14 x 2m long track sub-sections separated by 0.5m buffer zones of clean ballast (Geclexite was used to on each side of these buffer zones). Details of these sub-sections are as follows:

- 11 sub-sections with mixtures of clean ballast and coal fines, with PVC values of 0% to 100%, increasing in 10% increments, representing typical coal fouling,
- 3 sub-sections with mixtures of unscreenable and clean ballast (25%,
50% and 75% of unscreenable ballast), representing degraded ballast.

The ballast depth below the base of sleepers in this test track panel was 300mm.

Ballast for this track panel was placed directly on natural ground without any specific capping layer. However, as GPR data was only required from within the ballast layer (processing depth of 530mm from the top of sleepers to the base of the ballast layer) for this GPR-PVC calibration, the type of soil material below the base of the ballast layer was not considered to be important.

A photo of this calibration track panel is shown in Figure 6, with clean sub-sections and the GPR equipment at the far end of the track panel, and sub-sections with higher PVC values towards the foreground.

Figure 6: GPR PVC calibration track panel

This track panel was tested with GPR equipment before and after being flooded with water (water was used to wash fines to the base of the ballast layer, to represent typical accumulation of fines at the base of the ballast layer in the field).

GPR captured data was compared with results of PVC tests from PVC samples obtained from each sub-section, to develop a GPR-PVC calibration curve.

Following these calibration works, GPR PVC values were available at the three GPR testing offsets (track centre, and near both ends of sleepers), at 5min intervals.

ZeticaRail's GPR equipment measures ballast fouling levels by identifying voids within ballast. This method is not influenced by the ballast fouling material. These voids can also be identified whether they are filled with moisture or not.

2. GPR PVC values

ZeticaRail have used GPR antennas with the following frequencies on the QR National network:

• 2GHz: primarily for measuring ballast fouling levels,
• 400MHz: primarily for measuring ballast depths.

GPR data has been captured at speeds of up to 80km/h, with GPR equipment fitted to rail vehicles. At this data capture speed, these rail vehicles can travel at speeds to simulate real rail traffic, resulting in minimal disruption to rail traffic and no track closures required.

By the end of 2011, QR National had performed GPR testing on all four coal systems (track length of approximately 2000km) resulting in processing of approximately 1.1 million PVC values.

An example of a GPR chart with GPR PVC values is shown in Appendix A. PVC categories on the "1D-BFR" plot on this chart are as follows:

• clean (green): PVC: 0 to <10%,
• moderately clean (yellow): PVC: 10 to <20%,
• moderately fouled (orange): PVC: 20 to <30%,
• fouled (red): PVC: 30 to <50%,
• severely fouled (purple): PVC ≥ 50%.

Note on this GPR chart the distinct change in ballast fouling levels at 45.700km, with generally highly fouled ballast from 45.000km to 45.700km, and generally clean ballast from 45.700km to 46.000km. The information on this chart coincides with recent ballast cleaning on this track section, between 45.700km and 46.000km in July 2010.

BALLAST CLEANING PLANS

The method for developing the ballast plan is as follows:

1. divide each track section in sub-sections with generally similar average PVC values (including individual sections for each track on duplicated track sections. The minimum length of these sub-sections is 1km, which represents generally the minimum desirable length of ballast cleaning works at a particular location from a logistics viewpoint.

2. obtain the date of the most recent ballast cleaning works,

3. determine the duration and rail traffic level between the most recent ballast cleaning works and the GPR data capture date,

4. determine the ballast fouling rate per year and per Mnt of rail traffic,

5. determine theoretical rail traffic level (Mnt) until 30% PVC ballast cleaning intervention will be (or was) reached, and corresponding theoretical date,
6. Rank sub-sections in order of proposed rail traffic levels until intervention level reached.

Note that:
- average PVC values are assumed to be 5% after ballast cleaning, based on GPR data captured just after ballast cleaning works (or 0% if average PVC value for a subsection is less than 5%).
- on duplicated track sections, the total rail traffic level for the corridor is considered for calculation of ballast fouling rates for both tracks, as coal fines can settle on either track on duplicated track sections, not just the track carrying loaded trains.

Ballast cleaning plans consist of tables of subsections for particular track sections. Information extracted from one of these tables is shown in Appendix B.

As this method is based on rail traffic levels, dates can be easily adjusted if proposed rail traffic levels were to change.

SCHEMATIC PLAN

Though not showing specific ranking of subsections, schematic charts with average PVC values within specific ranges have been developed, and an example is included in Appendix B. This type of chart can be used to identify where high fouling levels are located with parts of the rail network.

FURTHER DEVELOPMENTS

Developments planned to be investigated to further improve planning ballast cleaning are as follows:
- calculating ballast volumes, from ballast surface profiles measured with laser equipment and ballast depths measured with GPR,
- considering other track information track geometry data with PVC values,
- using GPR to locate buried objects in ballast that can interrupt ballast cleaning operations, such as rail offsets,
- assessing ballast screenability with GPR.

CONCLUSION

Maximising the availability of the rail network by optimising track maintenance works is a key priority for QR National. Removal of fouling material from ballast is one of the most capital intensive and intrusive of these maintenance activities.

The predominant ballast fouling material on the CQCN is coal fines, and QR National is implementing mitigation methods to prevent coal and other materials from fouling ballast, however thorough planning of ballast cleaning works remains crucial.

This new ballast cleaning planning method can be used to more accurately determine locations and programs for ballast cleaning, resulting in improved utilisation of ballast cleaning resources, reductions in maintenance costs, and improved network availability for operation of rail traffic.

This method was developed on a railway system with predominantly coal fouling of ballast, however could also be used on railways with other types of ballast fouling material.

REFERENCES

1. Selig and Waters, Track Geotechnology and Substructure Management, 1994
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Appendix A – Example of a GPR chart with PVC values
**APPENDIX B – Extract of a ballast cleaning plan, based on GPR Information from July 2011**

<table>
<thead>
<tr>
<th>SUB-SECTION NUMBERS</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACK</td>
<td>Down</td>
<td>Down</td>
<td>Up</td>
<td>Up</td>
<td>Up</td>
<td>Up</td>
</tr>
<tr>
<td>START KILOMETRAGE (km)</td>
<td>8.43</td>
<td>12.97</td>
<td>14.68</td>
<td>16.05</td>
<td>17.42</td>
<td>19.37</td>
</tr>
<tr>
<td>END KILOMETRAGE (km)</td>
<td>12.97</td>
<td>14.27</td>
<td>16.05</td>
<td>17.42</td>
<td>18.73</td>
<td>21.68</td>
</tr>
<tr>
<td>LENGTH (km)</td>
<td>4.54</td>
<td>1.30</td>
<td>1.37</td>
<td>1.37</td>
<td>1.31</td>
<td>2.31</td>
</tr>
<tr>
<td>GENERAL FOULING LEVEL FROM VISUAL ASSESSMENT OF GPR PVC VALUES</td>
<td>Fouled</td>
<td>Moderately Fouled</td>
<td>Moderately clean</td>
<td>Fouled</td>
<td>Moderately clean</td>
<td>Clean</td>
</tr>
<tr>
<td>AVERAGE PVC VALUES (%)</td>
<td>36.5</td>
<td>21.4</td>
<td>17.9</td>
<td>38.6</td>
<td>20.0</td>
<td>8.9</td>
</tr>
<tr>
<td>AVERAGE TONNAGE SINCE MOST RECENT BALLAST CLEANING (000nt)</td>
<td>406303</td>
<td>406303</td>
<td>548576</td>
<td>548576</td>
<td>548576</td>
<td>NA</td>
</tr>
<tr>
<td>AVERAGE PVC FOULING RATE (change in PVC % per 100Mnt)</td>
<td>8.72</td>
<td>8.72</td>
<td>4.01</td>
<td>4.01</td>
<td>4.01</td>
<td>4.80</td>
</tr>
<tr>
<td>RAIL TRAFFIC REQUIRED TO ACHIEVE PVC VALUE OF 30% (Mnt)</td>
<td>-74.11</td>
<td>98.47</td>
<td>301.65</td>
<td>-213.35</td>
<td>249.14</td>
<td>439.03</td>
</tr>
<tr>
<td>SUB-SECTION RANKING VALUE (EARLIEST DATE IS RANKING No. 1)</td>
<td>15</td>
<td>47</td>
<td>97</td>
<td>5</td>
<td>85</td>
<td>108</td>
</tr>
</tbody>
</table>
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Appendix C – Schematic of part of a coal system with different PVC value ranges for 2010/2011