NOISE REDUCING SLAB TRACK FOR THE EPPING TO CHATSWOOD RAIL LINK

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SUMMARY

At CORE 2004 the authors presented a first paper on the control of Noise and Vibration on the Epping to Chatswood Rail Link (ECRL) project. That paper considered design requirements, the approach to acoustic modelling and preliminary track design. Given the position in the project programme, the paper stopped short of detailed design and construction issues. There has been much development in the intervening 4 years and this second paper completes the story, highlighting the processes used for validating the acoustic model, detailed engineering design issues, construction methodologies and the resolution of construction problems encountered.

With commissioning of the project ongoing throughout 2008, this paper provides an update on the refinement of the proposed extent of track treatments (use of track types) through research and site-specific testing to validate the acoustic model, including ‘ground’ propagation tests to provide a more accurate assessment of the vibration propagation characteristics of the rock along the tunnel’s route and further measurements of input vibration levels at the rail / wheel interface. This latter work will be used to give an overview of the impact of track maintenance on generated vibration levels.

In addition to the acoustic design, the paper considers the structural design of the slab systems, including the development of specifications for rail fasteners and slab bearings. It goes on to present a summary and findings of the debate on the use of ‘long’ versus ‘short’ (mini) slab Floating Slab Track (FST) systems and the innovative internal ‘bracing key’ concept adopted for the lateral and longitudinal restraint of the slabs. The paper concludes with a discussion of the construction methodologies developed for both Direct Fixation Fastener (DFF) and FST slab types, highlighting the issues and problems encountered during site operations and any problems were solved. As a final footnote the paper examines the last remaining area of work – validation testing under full service conditions.

1. INTRODUCTION

ECRL is one of the largest new rail infrastructure projects in New South Wales since the 1920’s. Developed and sponsored by the NSW Government, it is being delivered by the Transport Infrastructure Development Corporation (TIDC).

The main design and construct contract was let to the Thiess Hochtief Joint Venture on 6th July 2002. The new line will be fully integrated into the Sydney metropolitan network on completion. Works commenced on the contract on 25th November 2002 and will be available for the commencement of revenue services on completion of the current commissioning phase.

The project has been planned as an integrated link with between rail and other land transport systems, providing the two-fold benefits of access to developing areas of industry, commerce and education, as well as adding capacity to the rail network. The project corridor, key station locations and design requirements have been driven by an integrated land use and long term transport planning approach, treating this project as a first stage of several planned systems expansions.

Land use varies between commercial / industrial and residential purposes, with some very sensitive sites in terms of allowable levels of noise and vibration. Consequently, the success of the project hinges on full compliance with the stringent noise and vibration goals – our objective is to ‘quietly interface with the community’.
2. THE STORY SO FAR……

In our first paper we summarised the allowable targets the design had to deliver against for allowable ground borne vibration and regenerated noise within receptors. It is worth reminding the reader of these:

<table>
<thead>
<tr>
<th>Receiver / Receptor Type</th>
<th>Regenerated noise LAmax Fast Response (dBA re 2x10^-5 or Noise Rating Number as noted.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>35 dBA</td>
</tr>
<tr>
<td>Offices</td>
<td>40 dBA</td>
</tr>
<tr>
<td>Educational</td>
<td>40 dBA</td>
</tr>
<tr>
<td>Places of Worship</td>
<td>35 dBA</td>
</tr>
<tr>
<td>Cinemas, Public Halls &amp; Lecture Theatres</td>
<td>35 dBA</td>
</tr>
<tr>
<td>Film or Television Studios</td>
<td>25 dBA (NR 15)</td>
</tr>
</tbody>
</table>

*Figure 1: Allowable regenerated noise levels*

Basic track types were developed to provide a level of performance in vibration attenuation identified from acoustic modelling. The acoustic model considered a variety of variables as noted in figure 2:

*Figure 2: The Acoustic Model*

Modelling demonstrated that for long sections of the line, a DFF slab construction would be satisfactory, but that in limited areas a more sophisticated FST construction would be needed to meet desired goals. Preliminary designs for the two slab types had been developed to a level where their performance was well understood. At that stage, whilst some of the variables in the acoustic model were well defined and understood (such as the location, type and properties of the receptors), two key variables had been based on historic, non site specific, data. We take up the story at this point and look at research and further fieldwork undertaken to better define these areas of uncertainty and allow the ‘fine tuning’ of the model.

There were two main areas of research:

a) Ground Propagation Tests

A series of ‘ground’ propagation tests were developed to provide a more accurate assessment of the vibration propagation characteristics of the rock along the tunnel’s route.

b) Vibration Input Tests

Further measurements of input vibration levels at the rail / wheel interface were also undertaken. Conducted periodically over 18 months in the Sydney underground network, these tests provided data on the impacts of track maintenance (specifically rail grinding) and gave a good understanding deterioration rates for generated vibration levels. Outputs allowed the recalibration of the design input noise spectrum, ensuring that vibration goals would not be exceeded even when track condition reaches maintenance intervention levels.

3. GROUND PROPAGATION TESTING

One important input required for the acoustic model relates to the vibration propagation characteristic of the ground between the tunnel and the noise sensitive receivers nearby. The vibration characteristics of the ground depend primarily on the type of ground material - in this case, rock.

The most common method of measuring ground characteristics is to carry out testing along the proposed route of the rail tunnel, normally called “borehole” testing. This involves drilling a borehole or making use of an existing borehole to carry out the tests. The borehole should be to the depth of the base of the tunnel.

The test process involves applying an impact at the base of the borehole whilst simultaneously measuring the resulting vibration levels on the surface at a range of distances from the proposed tunnel. To apply the impact at the base of the hole, the most common approach is to apply the impact at the top of a series of drill rods, so that the drill rods transfer the impact to the base of the hole. A force transducer can be used at the base of the drill rods to measure the force that is imparted in the ground.

It is reasonably well understood that there are limitations in the accuracy of the borehole testing for the following reasons:

- It is difficult to get good coupling between the force transducer and the ground at the base of the hole and often the rods touch...
the sides of the borehole, sometimes resulting in inaccurate measurement of the imparted force.

Any vibration characteristics of the ground measured during the testing will potentially change after the tunnel is constructed.

Given these limitations, ground propagation testing carried out from within an already constructed, or partly constructed, tunnel is a better option, as this tends to give more accurate results than borehole testing. A slight variation on this approach was adopted for ECRL. It relied on the consistency in the properties of the sandstone rock found across the bulk of the Sydney area. Instead of borehole testing, the following approach was adopted:

- In the pre-construction phase ground propagation characteristics were measured from an existing rail tunnel within similar sandstone in the Sydney area (simultaneously with measurements of vibration input levels). This allowed the preliminary design of the track forms and an initial extent of those track forms for the project.

- Once construction of the ECRL tunnels was well advanced, further site specific ground propagation testing was carried out from within the bored tunnel prior to installation of the track work. The results of this testing allowed fine tuning of the extents of the track forms for the project.

This general approach was supported and supplemented by some limited borehole testing at one end of the proposed tunnel prior to construction in an area where rock other than sandstone was found. However, this paper covers primarily the testing from the existing tunnel and the testing from the bored ECRL tunnel.

### 3.1 Testing from Existing Sydney Tunnels

Sandstone rock propagation characteristics were determined from testing within an existing Sydney passenger rail tunnel, using the existing train movements as the vibration source, rather than special impact methods. This approach had a realism which normal borehole testing cannot replicate.

During the passage of trains in the existing rail tunnel, vibration measurements were carried out on the invert of the tunnel and simultaneously within nearby buildings, particularly within the basements of those buildings. The vibration levels measured on the invert were readily converted to vibration input levels (expressed as force density levels) as discussed below, after mobility testing of the invert was carried out. The difference between the force density levels and the vibration levels at the receiver locations gave a measure of the ground propagation characteristics (transfer mobility).

The measurement locations in nearby buildings were at a range of chainages along the length of the line, but Figure 3 summarises where these locations were in relation to the alignment of the tunnel.

![Figure 3 Locations of Vibration Monitoring Locations Relative to Tunnel](image)

At the early stages of the process the ground vibration characteristics were expressed as excess attenuation. A train travelling through a tunnel is a vibration line source and the standard form of propagation of vibration through the ground (geometric spreading) is cylindrical. This dictates the standard distance attenuation relating to geometric spreading. However, in addition to this, excess attenuation normally results from the damping characteristics of the ground. It is this excess attenuation that was determined from the existing tunnel testing. Figure 4 shows the excess attenuation determined for three of the main measurement locations.

![Figure 4 Excess Vibration Attenuation per 10m of Rock](image)
the third location was substantially higher. This is typical of such measurements, where micro-
conditions of the rock can substantially increase the attenuation. In this case, the lower excess attenuation at UAH1 was adopted for the design. On this basis the measured ground propagation values were used in the acoustic model to calculate noise and vibration levels, and to determine the most suitable, and preliminary extent of, track forms.

3.2 Testing from the ECRL Tunnel

After the ECRL tunnels had been constructed, but before the track work was installed, additional measurements were carried out at four positions along the length of the tunnel. The test locations were chosen to coincide with noise sensitive surface locations.

A special test rig was developed to impart an impact to the invert of the tunnel. Resulting vibration levels were measured at a series of locations on the surface at different distances from the tunnel. At one of the positions, the impact was applied at a series of points on the invert to simulate the length of the train and, in each case, separate simultaneous surface vibration measurements were carried out. The impact test rig used within the tunnel is shown in Figure 5.

Figure 6 shows the measured point source transfer mobility and the calculated line source transfer mobility at one of the positions, Essex Street. This location is the most sensitive location along the whole length of the tunnel.

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The line source mobility at each position was then incorporated into the model to recalculate the noise and vibration levels, for fine tuning of the extents. These levels were found to be very similar to those predicted from the ground propagation characteristics determined from the existing tunnel, and no change to the track form extents was necessary. This outcome results from the fact that the sandstone at the existing tunnel was the same as that at the ECRL tunnel.

4. VIBRATION INPUT TESTING

The Project Works Brief requires that “consideration must be given to performance degradation over time and identification of methods of inspection, repair and replacement of each trackform.”

In the acoustic design, particular consideration has been given to ensuring the necessary level of system attenuation and performance is maintained between maintenance cycles, during which time it is reasonable to say that track (contact surface irregularities) and rolling stock (wheel profile and tread irregularities) will experience some degradation and thus potentially increase the noise and vibration levels generated by the system.

The level of degradation of both track and wheelsets is reflected in the train generated vibration levels – one of the key variables in the acoustic model. Well maintained rail and wheel surfaces will tend to generate lower levels of vibration, whereas, rail and wheels with poor surface conditions will produce higher levels of vibration.
As the input vibrations in the model are measured over a wide range of frequencies, they are referred to as input 'spectrum'. The Project Works Brief contained a 'reference' spectrum for initial design purposes, but the Project Brief also required that suitable field-tests in similar ground conditions and with similar track types to those envisaged for the project should be undertaken to refine the design. This subsequent output would become the 'design' spectrum.

The initial 'design' spectrum was established by undertaking field measurements at several suitable locations in the existing (Sydney) City Underground Railway.

![Figure 7 Comparison of reference spectrum (red) and initial design spectrum (blue)](image)

When the Project Brief and initial design spectra were compared, it was found that the former indicated significantly higher levels of input vibration. It was established that this elevated input level was due to the deterioration of both rail and wheel condition over the long term maintenance cycle, i.e. a deterioration in rail head condition over the period between the measurements taken to establish the reference spectrum and the initial design spectrum. This is indicated in fig 7.

The difference in the 2 spectra naturally led the design team to consider if field tests had been accurate and also what the worst design case should be. So to validate a final design spectrum, further field-testing was suggested. In preparing for further testing, it was noted that rail grinding and general track maintenance had not recently been completed in those sections of the City Underground where the initial design spectrum had been measured. It was also noted that there was some evidence of corrugations at the main test site.

Recognising that there will be a significant range of values for the vibration spectrum, reflecting the track condition depending on the point within the maintenance cycle, it was noted that for the optimum design the spectrum should reflect track and rail head condition at the point when scheduled maintenance / rail grinding is due. To establish a final design spectrum it was decided that further field-testing in the City Underground Railway would allow more accurate prediction of design spectrum. Further testing was undertaken in September 2004. The final design spectrum includes an allowance for the ameliorating effect of grinding and the subsequent deterioration of rail condition before the next scheduled grinding.

In the September 2004 tests, arrangements were made to have the rails over a section of the test track ground to ascertain the effect that this would have on vibration input levels. Tests were carried out at one of the previously used locations (UAH2).

Prior to grinding, the vibration levels on the invert were re-measured (before measurements). After grinding, time was given for the rail head to settle in and the first set of after measurements were carried out three months after grinding. A final set of measurements was carried out eight months after grinding.

As we expected, the vibration levels measured just before grinding (before spectrum) were very similar to the initial set of measurement results (initial spectrum). After grinding, lower vibration levels were measured. After three months, the vibration levels in the most important frequency range (63-250 Hz) were in general approximately 10 dB lower. After eight months from grinding, the levels had increased by approximately 2 dB. Figure 8 shows the 95th percentile vibration levels measured on the invert:

![Figure 8 95th Percentile Vibration Levels, Invert Location (80 km/h)](image)

The after measurements also show a characteristic increase in level at approximately 400 Hz, and this increase is probably due to uneven grinding process of the rotational grinder which causes a type of corrugation over a small wavelength (40-50mm). Nevertheless, the higher ground attenuation at 400 Hz means that this increase is of little consequence at the noise sensitive receiver locations.

Although it is clear from these results that rail condition affects the resulting vibration levels and, therefore, likely noise levels in the surrounding area, the extent of the effect needed further consideration.
The acoustic model was used to predict approximate regenerated noise levels in buildings at a range of distances from a typical tunnel, based on the different vibration input levels. In this case, the modelling was simplified and constant factors such as coupling loss were eliminated from the model. Figure 9 shows then 95th percentile noise levels predicted for a range of distances from the tunnel.

Figure 9 95th Percentile Calculated Regenerated Noise Levels (80 km/h)

For locations within 20 m of the track, 95th percentile noise levels for the eight month case are approximately 3 dBA lower than the before case. At distances greater than 20m, the difference is greater. Even these small differences in dBA level would have a substantial effect upon the extent of the different track forms for the project, and it is therefore necessary to refine the vibration input spectrum for the project. Assuming that rail grinding occurs at intervals as required by the operator’s relevant standard (RailCorp Standard C3200), the worst-case rail condition can be taken to be equivalent to the rail condition approximately 12 months after grinding. Since no field measurements were actually taken 12 months after grinding, the ‘12-month’ spectrum was estimated. The estimate took the ‘8-month’ spectrum and added the difference between the ‘3-month’ spectrum and the ‘8-month’ spectrum. This assumes a slightly faster rate of deterioration in the final four months, which is considered realistic given that imperfections in the rail may tend to generate further surface damage at that point.

Figure 10 shows the design spectrum ultimately used for finalising the design (the ‘12-month’ spectrum), adjusted to 18 m, along with the original reference spectrum. The design spectrum is higher over the main frequencies than the original reference spectrum.

5. TRACK SLAB TYPES

With a revised acoustic design, the engineering design was reviewed and completed. In addition to developing specifications for rail fasteners and slab bearings, there were several areas for review and analysis.

During the preliminary design phase up to 5 different track types were considered, each with increasing levels of acoustic performance. However, as noted earlier, we found that the selection of a medium performance Direct Fixation Fastener (DFF - with up to 15 dBA attenuation) and a high performance Floating Slab Track (FST – with up to 24 dBA attenuation) offered the most cost effective, but technically compliant solution.

5.1 The Direct Fixation Fasteners (DFF) Trackform

A simple slab construction was chosen. This comprised a reinforced concrete slab laid directly onto, and dowelled into, the prepared tunnel invert:

Figure 11 Typical DFF Cross Section in Bored Tunnel
The sides of the track bed were left open to provide wide, easily maintained, drainage channels. Concrete reinforcement rates are relatively low and intended mainly for crack control rather than flexural capacity. Given that the design life required for the track bed is 100 years, a concrete mix with good durability characteristics was selected and which has a minimum 28-day strength of 32 MPa.

After reviewing several alternatives, the Delkor ‘Sydney Egg’ – a variant on the ‘Cologne Egg’ was adopted as the preferred rail baseplate. Developed for use on the Sydney Harbour Bridge and in the existing City Underground, these give a high level of performance. The required performance of the baseplates is shown in figure 12.

<table>
<thead>
<tr>
<th>Secant Static Vertical Stiffness</th>
<th>Maximum Vertical Deflection</th>
<th>Maximum Vertical Load without Failure</th>
<th>Maximum Dynamic/ Static Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 – 14 kN/mm at 20-35 kN load</td>
<td>4.5 mm at 35 kN load</td>
<td>90 kN</td>
<td>1.4 at 20 kN/load</td>
</tr>
</tbody>
</table>

*Figure 12 Performance Specification for Rail Baseplates*

Baseplates are fixed using galvanised screw spikes inserted into nylon ferrules cast into the track slab.

A ‘top down’ construction technique was adopted. This calls for the slab reinforcement and formwork to set up and then for the rails, complete with baseplates and fixings, to be suspended to line and level. When all components are correctly positioned, the concrete is poured and allowed to flow up to the underside of the baseplate before being ‘finished’. The rails are held in position by a series of screw jacks and clamps called ‘iron horses’, which also allow for the fine adjustment of line and level. A test section of track was constructed in the Contractor’s site depot – a useful exercise through which construction problems could be ironed out before starting work in the confines of the tunnel. Figure 13 shows the test section of slab set up and ready for pouring and figure 14 gives a view of the completed slab.

In the test slab, the process proved relatively straightforward, but highlighted issues that when constructing in the confines of the tunnel might prove problematic. The main issue identified with this type of construction technique, and one that might prove a real issue in the tunnel environment, was the avoidance, or minimisation, of air voids under the baseplate. With only a limited head of concrete above the underside of the baseplate, careful placement and vibration of concrete is required to avoid excessive voiding.

*Figure 13 Test Track (note rails and baseplates suspended from ‘Iron Horses’)*

Following the test track construction, the rails were removed and the baseplates lifted for inspection. In all cases, air voiding was present to a lesser or greater extent. It was always envisaged that some voiding would be allowed and that up to 30 % of the area below the

*Figure 14 End view of completed DFF track slab*

*Figure 15 Voiding under the baseplate*
baseplate could be voided without any loss of performance or structural stability. A typical result is illustrated in figure 15. All of the baseplate ‘footprints’ were examined using scale photographs with an overlain grid to determine the size, distribution and an overall percentage of area of the voids. A standard for the acceptable limits for these features was developed and agreed. From this exercise a range of sample photographs was made available – effectively a ‘handbook’ of acceptable, or ‘pass’ prints. These were used to support a rigorous sampling, inspection and QA process. Figure 16 shows a typical ‘pass’ example.
The QA and sampling process was intended to limit degree of voiding (expressed as a % of the bearing area) and to ensure that no single void was allowed to exceed an agreed maximum dimension. Any non-compliances, led to the whole inspection section being lifted and repairs being carried out (using a trowel applied epoxy grout mortar).

5.2 The FST Trackform

FST carries the rails on a reinforced concrete slab that is itself acoustically isolated from the tunnel structure and the surrounding ground mass. Isolation is provided by means of suitable acoustic bearings (usually laminated rubber and steel), with such bearings being arranged to provide both vertical support for the slab as well as lateral and longitudinal restraint – in effect the track slab ‘floats’ like an independent bridge structure within the tunnel. For economy and to fit within the spatial constraints of the tunnel, a slab 2.15 m wide and 300 mm thick was identified. The length of slab was open to debate. The design team favoured a relatively long slab (of around 20 m), whereas several recent projects in Asia and Europe had offered a short, or ‘mini slab’ design. This latter option generally has a slab length of about 2 x the normal rail baseplate spacing (about 1.2 – 1.4 m). A typical mini slab solution is shown in figure 17. To resolve the issue and to allow the design to process, dynamic modelling of both mini slabs and long slabs was carried out to determine relative performance levels. Even though the long slab was considered more cost effective, it was important to establish the vibration attenuation characteristics of both types of slab. A finite element model was prepared for each type of slab and the dynamic characteristics studied.

![Figure 16 A sample of a ‘Pass’](image1)

![Figure 17 A typical ‘mini slab’ installation](image2)
the long slab being selected for detailed design and construction. The slab length chosen was 19.250 m – this was close to the nominal 20 m long slab modelled, but consistent with the chosen baseplate spacing of 700. Lateral and longitudinal restraint is provided at 7 m intervals along the slab and the slab is supported on elastomeric bridge type bearings under every 3rd baseplate position (i.e. at 2.1 m centres). This layout is shown in Figure 18 following.

5.2.1 The internal ‘bracing key’ concept
In a conventional FST arrangement, lateral restraint for the slab is provided by ‘side walls’, which enclose the slab as shown in the example in figure 19 or the mini slab solution shown in figure 17.

This approach frequently poses several longer term maintenance and performance issues and in recognition of this, the ECRL project Works Brief required that any design must consider, and suitably address, the problems of:

**Access** - for both ongoing inspection and future maintenance of the track slab and bearings - a particular requirement was to ensure that all bearings could be later removed, inspected and replaced (i.e. for possible upgrading should higher levels of attenuation be desirable).

**Ongoing performance** – central to achieving this is ensuring that there is a clear unobstructed airspace under, and around, the slab. Any bridging of the airspace, or over compression of trapped air in this space, can provide a path for vibration to propagate and so reduce overall acoustic performance. In enclosed systems, the under slab void can become ‘clogged’ by rubbish, drainage sediment, or filled by water if not adequately drained. Drainage is a critical feature – in enclosed systems it is difficult to provide accessible and easily maintained drains (for both track and tunnel seepage), as the lowest drainage path is invariably below the track slab.

**Simplicity of construction** – especially in the confines of the tunnel - this must also recognise that slabs will not generally be straight, but will follow the track alignment both horizontally and vertically and that their upper surfaces will have to be profiled to match the required superelevation to be applied to the track through horizontal curves.

![Figure 18: Cross Section (above) and Plan (below) of ECRL 'Long Slab'](image)

![Figure 19: Conventional FST Construction](image)
The design team recognised that to achieve these features, the design must find a way to avoid enclosing the slab – in effect sidewalls would not be allowable. This posed the problem of how lateral restraint (and to a lesser extent, longitudinal restraint) could be provided. The solution developed was both simple and effective – restraint would be provided within the slab itself. It was noted that apertures could be readily formed in the slab, and that the slab could ‘bear’ onto a reinforced concrete ‘bracing’ key that could be built into the tunnel invert, but passing through the slab apertures.

With the resulting open sided slab arrangement, the airspace below the slab could be readily inspected and cleaned, as well as easily drained. Drainage, and simple construction, was further promoted by the casting of a ‘topping layer’ directly onto the tunnel invert to form an even surface on which the track slabs could be match cast and then being jacked into final position. The topping layer effectively also forms a shallow, but wide, drainage channel on each side of the slab. Being lower then the topping layer, the resulting side drains, promote free drainage below the slab. The construction of the slab and the bracing key is shown in figures 20 and 21:

As match casting and jacking of slabs became part of the construction sequence, the ability to jack the slabs provided the answer how the vertical support bearings could be subsequently be removed for inspection or replacement – a very similar jacking arrangement could be used in the future to raise the slab off its bearings, which can then be manually removed and replaced. This is ability can be clearly seen in figure 22.

Jacking was made easier by casting sockets into the sides of the slab to allow the fixing of steel brackets to form jacking points. The use of simple formers placed on the topping layer, allowed for recesses to be cast into the underside of the slabs, providing a means of locking vertical support bearings into a fixed position when the slab was lowered.

With the slabs mounted on the vertical bearings and the lateral and longitudinal bearings installed in the bracing keys, the rails were installed. To meet the demanding tolerances in line and level, a ‘quasi top down’ construction technique was adopted. The process had similarities to the process developed for the DFF sections (see 5.1). Using this technique, the rail baseplates were mounted on an epoxy mortar pad, with holding down screw spikes and ferrules being cast into holes core drilled into the slab by using a template to mach the fixing positions in the baseplate.

Since the slab had already been formed, the cumbersome ‘iron horses; used in the DFF process, could be avoided and a simpler, but very accurate adjustment could be achieved by the use of simple screw jacks and bracing brackets. This is shown in figure 23.
Very few problems were noted during the construction of the FST, other than those stemming from the difficulty of logistics and operating in the confined tunnel site. The problem of ‘honeycombing’ below the baseplates was avoided with the FST, mainly through the quasi top down methodology and the use of a high strength, but very ‘pourable’ epoxy grout mix. The quality of grouting can be noted in figure 25. In all over 5 km of FST was constructed and how the track fits the overall tunnel context can be seen from figure 26.

**CONCLUSION**

Test trains have been running on the completed track structure at full design speed since April 2008. Initial feedback has been very favourable, with reports of good ride quality and noise attenuation. Final noise and vibration compliance testing is planned from mid 2008.

With no significant previous use of high attenuation non-ballasted track in Australia, the design process very much had to take a first principles and research led approach. Perhaps having no preconceived ideas assisted the design team to achieve a better understanding of the issues and so driving innovation. Certainly, this approach led to 2 key areas of innovation:

- Understanding the relationship between the rail condition, the rate of deterioration of condition and the impact this has on generated vibration levels, so allowing us to ensure that the design was neither optimistic nor pessimistic, but provided the a design that delivers compliance throughout the maintenance cycle’ and
- A FST track form that delivers on performance, serviceability and maintainability, whilst offering cost advantages over the more conventional approach.

In final summary, if there is one overriding lesson learned, it’s that solutions must be project specific and that a ‘one size fits all’ approach is not realistic.