PROPAGATION OF VIBRATION FROM RAIL TUNNELS: COMPARISON RESULTS FOR TWO GROUND TYPES

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Abstract

Detailed measurements of vibration transmission from an underground rail line in Sydney and a line in a deep cutting in Perth have recently been conducted. The propagation characteristics of these two ground types are very different, and neither fits comfortably with standard theoretical models of vibration transmission through a uniform ground. In Sydney, the results can generally be modelled as a vibration source slightly larger than the tunnel floor, propagating into a uniform medium, but with an attenuation rate which is much higher than expected for sandstone or similar rock. The additional attenuation may well be due to scattering from inhomogeneities in the rock, and hence may differ significantly between locations. In Perth, the only successful model is of two-dimensional propagation in a medium with almost no attenuation at low frequencies. These results emphasise the importance of on-site measurements in predicting vibration and structure-borne noise levels from rail tunnels.

Introduction

In urban areas, opportunities to provide new transport infrastructure are increasingly limited by space and environmental issues. This makes tunnelling a popular, if expensive, option for many new road and rail projects.

In the case of rail tunnels, possibly the most significant environmental impact is the potential for vibration and regenerated noise to be produced in sensitive buildings above. Regenerated noise, in particular, can result in adverse reaction from building occupants at relatively low absolute noise levels. In Australia, criteria for levels of regenerated noise in residences, for example, are typically 30-35dBA maximum noise level during a train passby.

Although effective methods exist to mitigate rail vibration, they are expensive and require compromises in other aspects of the tunnel design. Hence it is important to predict surface vibration levels accurately, to ensure that mitigation is used where it is necessary, but not where it is not.

Prediction methods inevitably involve three components:

- the vibrational force produced by a train on the tunnel structure;
- the attenuation of vibration between the tunnel structure and the ground surface; and
- the interaction between ground vibration and building structures, including the production of structure-borne noise.

The present paper considers issues related to the second of the above components. This is perhaps the most problematic, in that it depends on processes which are complex and not well understood. The paper presents the results of recent measurements, indicating that between-sites variation in propagation can be very large. The data are not sufficient to develop generally-applicable guidelines for prediction, but serve to put limits on the prediction accuracy of any general model.

Theoretical Considerations

Figure 1 shows a schematic depiction of the propagation of vibration from a rail tunnel.

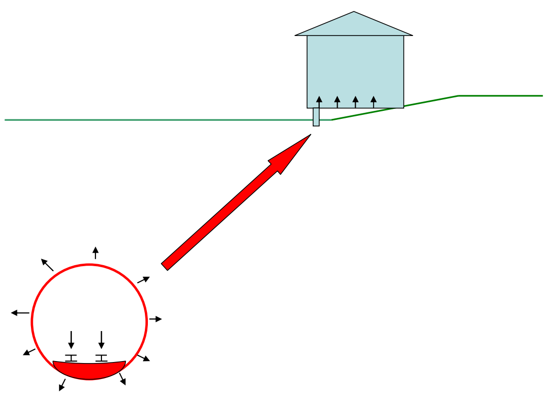

Figure 1: Vibration Propagation from a Tunnel

Vibration is generated at the wheel/rail interface by irregularities in the wheel and/or the rail. It is transmitted through the track fixing system, and any specifically-designed structures such as a floating track slab, to the tunnel structure. Although the tunnel structure is generally well coupled to itself, vibration levels can vary significantly around the structure.

From the tunnel, vibration enters the surrounding ground. In this process it may experience a “coupling loss” due to an impedance mismatch between the tunnel and the ground.

The processes by which vibration can be assumed to propagate in the ground are described in [1]. Vibration travels initially as bulk compressional and shear waves which for an omnidirectional line source theoretically attenuate as $10\log(d/R)$, where d is the distance from the tunnel centre and R is the tunnel radius. These waves will also experience viscous damping, which can be approximated by an attenuation of $27.3\eta f/c$ dB per metre where f is the frequency, c is the wave speed in the medium and η is a loss factor which is generally taken to be frequency-independent. This leads to attenuation being expressed in terms of "decibels per wavelength".

On reaching the surface, surface or Rayleigh waves are produced which for a line source experience no geometrical attenuation but do experience viscous damping (which may involve a loss factor different from that for bulk waves in the same medium).

However, there are also many other factors which are much more difficult to describe parametrically, or to predict from ground properties which are typically measured in geological surveys. These include diffraction and reflection of bulk waves from inhomogeneities in the medium, and scattering from small-scale irregularities [2]. Depending on the situation, these may attenuate or amplify vibration levels compared with the results of simple predictions.

Several attempts have been made to produce an adequate prediction of ground-borne vibration propagation using a semi-empirical approach in which approximate values are given to the various parameters mentioned above. An early approach [3] considers only bulk waves, and gives approximate values for η which correspond to attenuations of approximately 0.3dB per wavelength for rock and 3dB per wavelength for sand. Attenuation due to waves passing through a discontinuity between media is also considered, but not the effects of reflection or scattering from small discontinuities in the same medium. The approach used for the Channel Tunnel project, as described in [4], is similar, but allows for variable attenuation co-efficients for both bulk and Rayleigh waves, determined empirically. Reference [1] attempts to introduce further empirically-determined parameters representing the distribution between bulk and Rayleigh waves, and between point-source and line-source generation, but finds that with so many parameters the available empirical data is insufficient to pin them all down.

A validation study reported in [4] shows 95% confidence limits for the prediction accuracy of these semi-empirical models to be ±8dB for the A-weighted vibration velocity. This is considered typical for models which do not use site-determined parameters. More complex predictive procedures have also been studied, involving finite element modelling of a layered ground [5]. These have the disadvantage that numerous parameters are required to describe the properties of the ground structure. Even then, results in [5] indicate that predicted ground vibration at important frequencies can be in error by up to 10dB.

The above summary would indicate that without site-specific measurements of actual vibration propagation, design of mitigation measures would need to be very conservative to guarantee a required outcome.

Vibration Measurements - Sydney

Measurement Procedures

The Epping to Chatswood Rail project in Sydney consists of twin bored rail tunnels, each approximately 12km long, passing at many points under established residential areas. Because of the sensitivity of the project it was determined that specific measurement results were required to provide greater certainty in predicting vibration impacts than the generic models described above.

Measurements of rail vibration were conducted at seven sites in the Sydney Underground rail tunnel. The measurements were intended both to document the levels of tunnel wall vibration due to existing trains and to investigate the propagation of this vibration through sandstone typical of the Sydney area, including the Epping to Chatswood corridor.

Automatic measurement equipment was left in the tunnel for at least one day, and recorded all train passbys. Accelerometers were located:

- on the rail flange;
- on the tunnel floor immediately adjacent to the rail fastener;
- on the tunnel floor approximately 2m from the rail; and
- on a bracket attached to the tunnel wall.

At each site, some of the measured passbys were also monitored at one or a number of locations within buildings close to the track. This manual recording occurred only over a limited period, and hence the number of recorded passbys is lower. At the five sites of direct relevance in this paper, monitoring was performed on a rock face or on a slab laid directly on rock, below ground level. All accelerometers recorded vibration in the vertical plane only. Previous and subsequent measurements have confirmed that this is the dominant direction for train-generated vibration. Track fixings at each site varied between "direct fix" – with sleepers directly fixed to the concrete base – and Delkor "Alternative 1" and "Sydney Egg" rail fasteners.

Table 1 shows characteristics of these five monitoring sites, together with a sixth site which is used below for describing in-tunnel vibration. Figure 2 shows a representation of the location of each building monitoring position with respect to the track and tunnel structure.

Table 1: Characteristics of Vibration Monitoring Sites - Sydney

Site Code	Track Description	Track Fixing	Measured Passbys in Tunnel*	Building Measurement Location	Passbys With Correlated Building Vibration
32 York 2	Down Shore line near 32 York St	“Alternative 1”	107	Tiles laid on slab 4m below street level	28
UAH 1 (a)	Up Shore line near United Airlines House	Direct Fix	317	Carpark lowest level – slab on ground	16
UAH 2 (a)	Down Shore line near United Airlines House	Direct Fix	174	As above	27
ANA (a)	City Circle outer line near ANA hotel	“Sydney Egg”	102	Exposed rock in carpark 8m from track	31
ANA (b)	As above	“Sydney Egg”	102	Exposed rock in carpark 17m from track	31
QVB 1	Up Shore line near Queen Victoria Building	Direct Fix	32	[Not used for ground vibn. measurement]	-

* *Includes only passbys for which the train speed could be determined using vibration data*

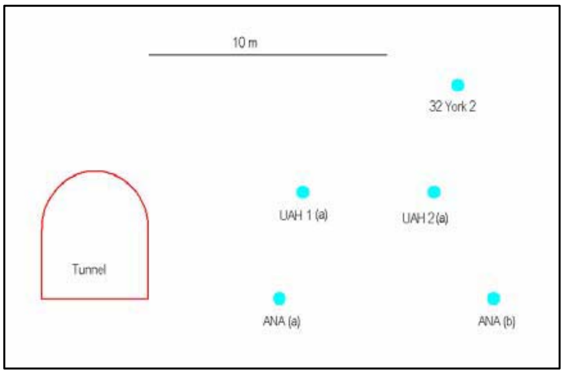

Figure 2: Schematic representation of monitoring positions, Sydney

Results – Vibration Within the Tunnel

Measured vibration levels were first corrected for train speed, which was measured by timing the vibration pulses from individual wheel-sets. Frequency-dependent relationships between speed and vibration level were derived, and these were used to correct all measured vibration levels to a train speed of 50 km/h.

Figure 3 shows mean vibration levels due to train passbys at 50 km/h for each of the four “in-tunnel” accelerometer locations, at two measurement sites with nominally the same track fixing and tunnel structure.

It is clear that at some sites such as “UAH 2a”, vibration levels can vary by over 10dB at different points around the tunnel, while at others such as “QVB 1” vibration is more uniformly distributed. This has consequences for prediction methods, as all the theoretical discussion above assumes that the tunnel acts as an omnidirectional source. In analysis, the “floor close to wall” location was taken as being generally representative of typical tunnel wall vibration. However, this represents a generalisation, and in particular, vibration levels directly over the tunnel are likely to be over-predicted.

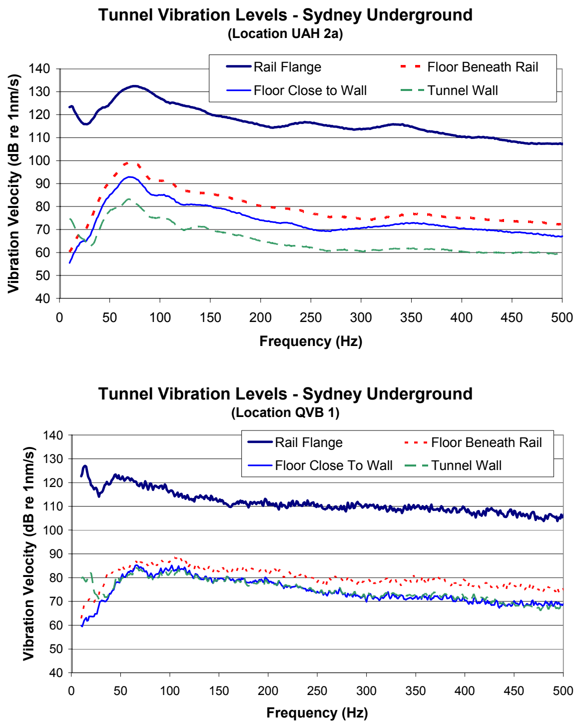

Figure 3: Narrow-Band Rail Tunnel Vibration Spectra at two sites – Sydney

Results – Through-Ground Propagation

Figure 4 shows differences between 1/3-octave band vibration levels measured at the "floor close to wall" tunnel location and the sites shown in Figure 2, determined for each train passby and averaged. (Variation in these differences between passbys was small except at frequencies below 16 Hz.) In general terms the results are reasonable – the attenuation is strongly frequency-dependent, suggesting damping is important, and the two closest sites, ANA(a) and UAH 1(a), have generally low overall attenuation. However, an unexplained resonance phenomenon is seen at ANA(a) at about 400 Hz, and the attenuation at ANA(b) is significantly lower than at other sites at a similar distance. The latter could be related to the fact that the ANA sites are lower with respect to the track than the others (Figure 2).

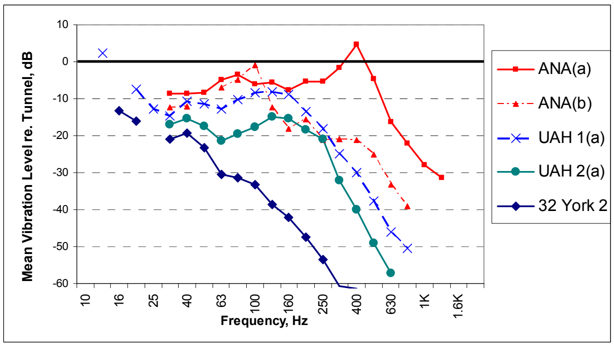

Figure 4: Third-Octave Band Attenuations - Sydney

In Figure 5, an attempt is made to fit a standard line-source-plus-viscous-damping model to the data from UAH 1(a), UAH 2(a) and 32 York 2. Measured attenuation values are corrected for line-source spreading, and then expressed as excess attenuation per 10m.

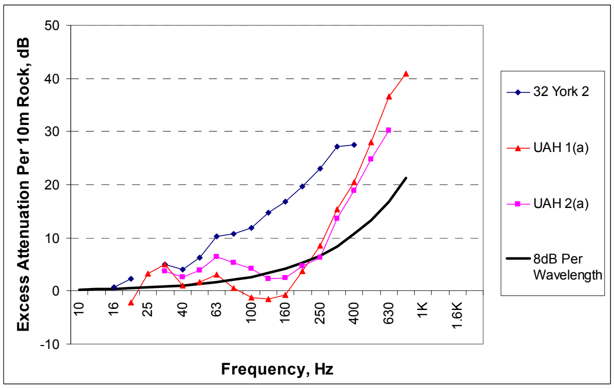

Figure 5: Excess Attenuation Per 10m Distance - Sydney

The values for UAH can be fit with an attenuation expressed as decibels per wavelength, while remaining generally conservative. However, the simple propagation model could hardly be said to be validated. It underpredicts the attenuation at 32 York, and overpredicts at the ANA sites (although these are of less importance in predicting propagation from a tunnel to the ground surface). Further, the "best fit" damping co-efficient of 8dB per wavelength is spectacularly out of line with published estimates for rock of about 0.3dB per wavelength.

It is likely that the excess attenuation seen in Figures 4 and 5 has less to do with damping than with scattering from small-scale fractures of the rock in these areas (given that there should be no significant layering), and that between-sites differences are due to differences in the amount and scale of fracturing. This implies that unless propagation measurements are made very close to the site of a potential tunnel, the best that can be hoped for from any model is a description of propagation in ground typical of the general area. This could be designed to be conservative, but may in some cases be conservative by up to 10dB, as at the 32 York site.

On the basis of the results reported here, at the time of writing this paper, detailed tests at a number of locations along the Epping to Chatswood route, using borehole techniques as well as testing in the partially-constructed tunnel, are being conducted.

Vibration Measurements - Perth

Measurement Procedures

The Perth MetroRail project includes twin bored and single cut-and-cover tunnels, approximately 1800m long, passing under the Perth CBD. Whereas in the Sydney project the tunnels are bored through sandstone, in Perth the ground is sand, clay or alluvium. Because there are no existing rail tunnels in Perth, exploratory measurements were conducted using deep cuttings at two sites to the north of the project area, referred to as the East Perth and Roe Street cuttings. These two cuttings were in sand which is typical of much of the route of the tunnel.

The measurement set-up was as shown in Figure 6. Once again, monitors on the track slab automatically recorded all movements for at least one day, while those at the surface recorded a sample of movements. Apart from the difference in ground type, other differences between these measurements and those in Sydney are:

- there is a possibility for the propagation of Rayleigh waves to the measurement positions, either directly from the track up the sides of the cuttings or via bulk waves reaching the surface and generating Rayleigh waves. Direct propagation is considered unlikely, as the sides of the cuttings contained very different materials from the track or the ground surface and hence there would have been a significant impedance mismatch; and

- the track slab is wider than in the Sydney tunnel, with two sets of tracks.

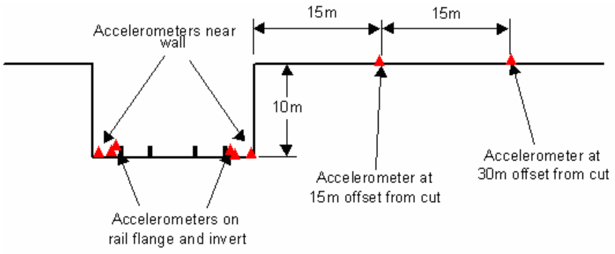

Figure 6: Schematic representation of Monitoring Positions, Perth

Vibration levels were corrected to a train speed of 50km/h as for the Sydney data. Figure 7 shows a comparison of measured vibration levels at the four "track slab" accelerometers at the East Perth site, for trains on the Down line. This illustrates a general feature of these measurements at both sites – at frequencies of most interest, between about 31.5Hz and 100 Hz, levels at the two accelerometers toward the centre of the slab were similar, and higher than those near the wall. This is despite the fact that one of the "central" accelerometers was directly beneath the track while the other was approximately 2m away. In analysis the mean of the two "central" accelerometer levels was used to represent the overall slab vibration level.

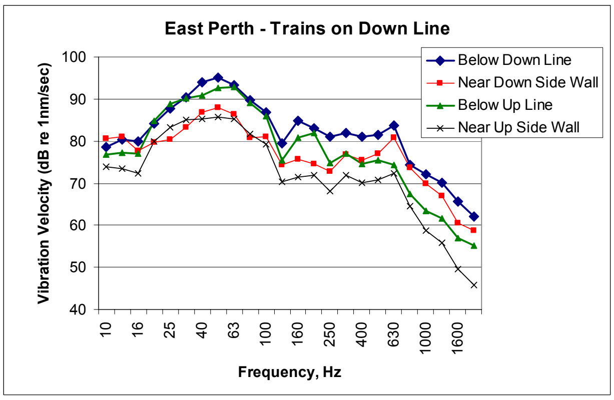

Figure 7: Example of Rail Track Vibration Spectra, Perth

Through-Ground Propagation

Figures 8 and 9 show differences between track-slab vibration levels and levels measured at the 15m and 30m locations shown in Figure 6. Figures 8 and 9 are directly comparable to Figure 4 for Sydney sandstone. They also show predictions from a simple line-source-plus-viscous-damping model, with a typical published value of 3dB per wavelength for viscous damping in sand[3].

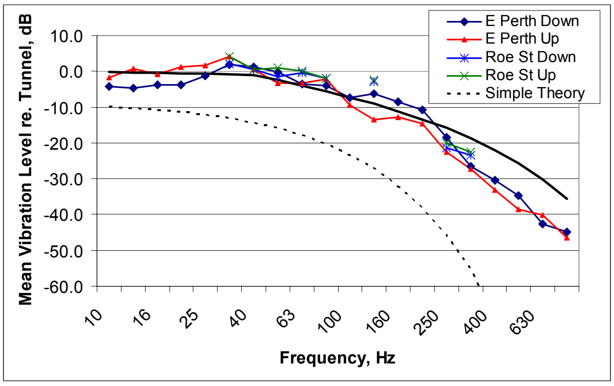

Figure 8: Third-Octave Band Attenuations in Perth - 15m from Cutting

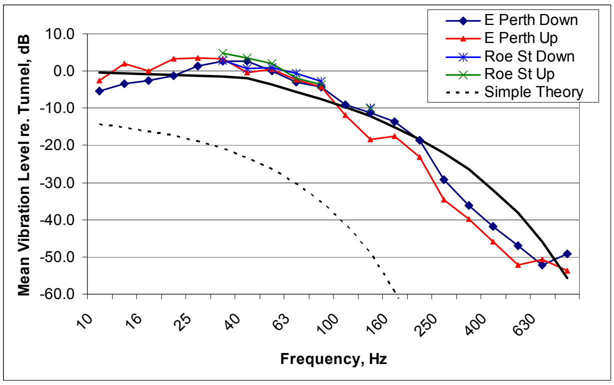

Figure 9: Third-Octave Band Attenuations in Perth - 30m from Cutting

Several features are apparent from these data. First, there is clearly no geometric line-source spreading within 30m of the track, at either site. Either the energy is propagating almost entirely as Rayleigh waves, or bulk waves are being constrained to a thin surface layer by reflection from a discontinuity. (This could conceivably be the water table.) Second, viscous damping is clearly much lower than standard theory would predict.

After some consideration, the model which provides the best fit to these data was found to include:

- no geometric spreading for distances which are short compared with the train length;
- a frequency-dependent coupling loss between the track slab and ground above 40 Hz; and
- a "damping" term equivalent to 0.5dB per wavelength. Once again, it is doubtful whether this actually represents viscous damping, or another attenuation process with similar frequency characteristics.

Predictions from this model are shown as heavy lines in Figures 8 and 9.

Although the measurement locations are relatively close to the tunnel location, and the results from the two sites are quite consistent, once again at the time of writing this paper attempts are being made to conduct measurements of vibration propagation at the exact tunnel location, to remove remaining uncertainties.

Conclusion

Models of wave propagation involving a combination of geometric spreading and some additional frequency-dependent attenuation are very familiar to acousticians. For atmospheric propagation, such models are generally acceptable, and at least conservative, although they are sometimes in error due to site-specific atmospheric or topographic effects.

The results presented above indicate that to describe the propagation of vibration from underground tunnels, such models should be used with extreme caution, if at all. Data from the U.K. suggest the prediction accuracy of such models could be about ±8dB (95% confidence limit), but the data above suggest that under the range of conditions applying in Australia the likely error is even higher, even for distances as close as 15m from the tunnel (see Figure 8).

To achieve better accuracy, the only available method appears to be to conduct measurements of vibration transmission in the exact location proposed for the tunnel, or as close to it as possible. Where there is an existing rail tunnel close by, this provides the ideal solution. Otherwise, techniques are available involving drilling a test bore hole, applying a known force at the bottom, and measuring the resultant vibration at the surface (see [6]). These have not, to the authors knowledge, yet been used in Australia, but are currently being planned.

References

[1] Verhas HP, "Prediction of the propagation of train-induced ground vibration", *J Sound Vib* 66(3):371-376, 1979.

[2] Heckl M, Hauck G and Wettschureck R, "Structure-borne sound and vibration from rail traffic", *J Sound Vib* 193(1):175-184, 1996

[3] Ungar EE and Bender EK, "Vibrations produced in buildings by passage of subway trains: parameter estimation for preliminary design", in Proceedings of Inter-Noise 75, 491-498, 1975

[4] Hood RA, Greer RJ, Breslin M and Williams PR, "The calculation and assessment of ground-borne noise and perceptible vibration from trains in tunnels", *J Sound Vib* 193(1):215-225, 1996.

[5] Jones CJC and Block JR, "Prediction of ground vibration from freight trains", *J Sound Vib* 193(1):205-213, 1996.

[6] Harris Miller Miller & Hanson Inc, "Transit noise and vibration: Impact Assessment". Report DOT-T-95-16 prepared fro Office of Planning, Federal Transit Authority, U.S. Department of Transportation, 1995.