The prediction and mitigation of vibration impacts of tunnelling

David Hiller

Acoustics, Arup, Manchester, England

ABSTRACT

This paper provides a state of the art review of the assessment of construction groundborne noise and vibration impacts that arise from subsurface works, which need to be identified and addressed in the planning, design and construction of tunnels. Through a review of published information and description of recent project-specific research, methods of prediction, assessment, measurement and mitigation of these impacts are described. The significance of any effects arising from these impacts is dependent upon the overlying receptors. Assessment for facilities ranging from nanotechnology to human comfort and building damage are considered, including recent work to establish acceptability criteria for construction works taking place adjacent to existing subway tunnels. The need to specify monitoring equipment correctly is discussed. Options for mitigating the effects of construction vibration are described.

INTRODUCTION

During the planning of new infrastructure projects, preparation of a robust environmental impact statement is essential to ensure the acceptability of the scheme. Tunnels are beneficial in minimising many of the impacts normally associated with linear projects, but there is potential for groundborne noise and vibration to affect people and properties above the entire tunnel corridor. This may be from both the construction and operation of the scheme.

It is therefore necessary to predict reliably the impacts and effects that may arise. The importance of this has been highlighted recently during the planning process for the Dublin Metro North in Ireland. The planning inspector's report (Moore, 2010:255) following the public enquiry noted:

> The Board could not, in my opinion, have taken any reasonable, balanced decision based upon such a glaring deficiency of reliable information against which the proposal could be measured.

Drawing on recent experience from the planning and construction of infrastructure tunnels, largely in the UK and Ireland, together with published information from elsewhere, this paper considers the latest applied prediction methods for vibration and groundborne noise during tunnel construction. Mitigation of the impacts is also considered. The focus is on bored tunnels, rather than those constructed from the surface, for which the impacts are more akin to many other forms of construction works, and for which there are commonly accepted prediction methodologies.

PREDICTING VIBRATION

Vibration during construction arises not only from the excavation method, which may be roadheader, full face TBM, backhoe, but also from other associated construction activities, some of which can be as disturbing, or more so, than the main excavation method. These include drilling (e.g. for blast holes), operation of temporary construction railways or compaction of cast *in situ* linings. The duration for which vibration impacts occur for these can be significantly longer than for the excavation *per se*, so the impacts may be potentially longer and hence more significant.

Prediction Methods

Prediction of groundborne noise and vibration may take either an empirical or an analytical approach. Numerical methods are used and may be either through application of commercially available software such as ABAQUS (for example see Rahman and Orr, 2011) or through development and application of bespoke software, such as that described by Thornely-Taylor (2004).

The UK, Transport Research Laboratory Report 429 (Hiller and Crabb, 2000) provides a simple empirical equation based only on distance from the source, but with a note that the vibration is dependent on geology, suggesting a factor of 10 difference (20dB) in PPV between tunnelling in rock and tunnelling in soft ground.

Orr and Rahman (undated) suggest that predictions can be improved by gaining a better knowledge of the site-specific ground conditions to allow material damping to be included and hence improve confidence in the predicted rate of attenuation of vibration. Given the inherent uncertainty in vibration predictions, clearly any refinement that provides greater confidence in assessments is beneficial. Such an approach may be better implemented once tunnelling has commenced, with the contractor obliged to take measurements at the early stages of driving to improve the reliability of initial predictions and, if necessary, update them. This enables sensitive receptors to be better prepared and plan sufficiently in advance for disruption and so that the tunnelling contractor can plan and minimise any necessary interruptions to the works.

The conclusion reached from the tunnelling data in TRL 429 was that it is the ground being excavated, rather than the excavation method or bore size, that dictates the magnitude of vibration quantified in terms of PPV. The corollary of this is that, once the tunnel route has been decided, there is little that can be done to reduce the levels of groundborne noise and vibration. Relocation of the tunnel is one option, either vertically or horizontally. However, increasing the depth of the tunnel may be counterproductive, if in so doing the tunnel would be required to be driven in rock rather than shallower, softer material. The consequent increase in vibration due to the excavation of harder material may not be offset by the greater distance from sensitive receivers.

Whatever approach to prediction is taken, it is essential that it is validated against real measured tunnelling data. In the recent Expert's Report to the Dublin Metro North public enquiry (Massarsch, 2010:58) it is noted that:

> Theoretical models are not sufficiently reliable to predict vibration propagation from different sources of construction activities through geological formations. Therefore, predictions of vibrations and groundborne noise presented in the EIS [Environmental Impact Statement] are preliminary in nature and must be verified by field vibration measurements. Prediction models need to be calibrated against and updated based on field trials.

Excavation

As noted above, the material being excavated appears to dominate the vibration (quantified in terms of peak particle velocity, PPV) that arises during a tunnel drive.

Hiller and Crabb (2000) presented field data measured at a number of sites by TRL and some additional data compiled from other published sources. Figure 1 (adapted from the report) classifies the data according to the geology through which each tunnel was driven and includes additional data from tunnelling in Ramsgate, UK.

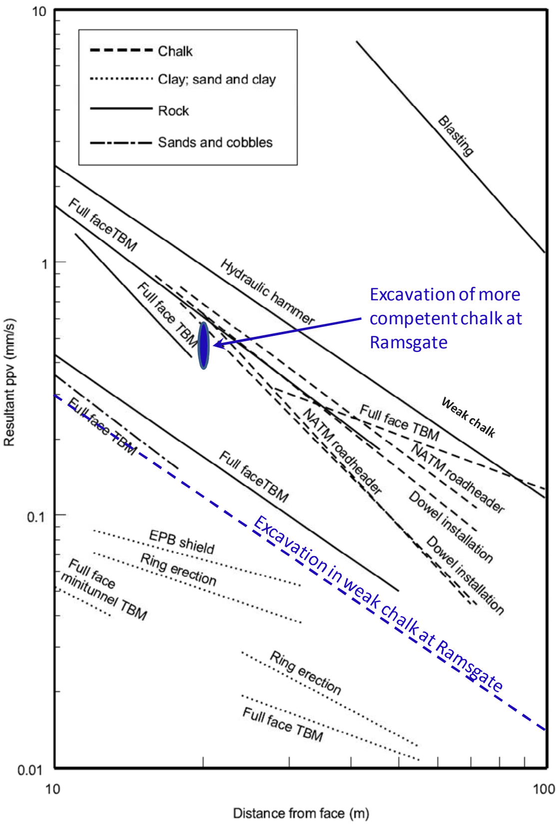

Figure 1. Tunnelling vibration data classified according to geology (Hiller and Crabb, 2000, amended).

It is clear from Figure 1 that, in general terms, the vibration increases as the strength of the ground through which the tunnel is bored increases:

- The lowest data are from tunnelling in clays and sands and clays;
- Tunnelling through chalk, (a weak, fine grained limestone), causes an intermediate level of vibration;
- Excavation of more competent rocks generates the highest vibration; and
- Where blasting is required, vibration (in PPV terms) from explosive detonation is higher than from any of the mechanical sources.

The data from the chalk sites are worthy of further consideration. The chalk data include:

- Full face c. 8.7m diameter TBM;
- Roadheader – which excavates the face a small area at a time; and
- Drilling for dowel installation to secure blocks of rock where jointing presented a risk of failure before the lining was installed.

Despite the range of activities, the chalk data are very closely grouped when compared to the entire dataset comprising the various geologies.

The additional data from chalk tunnelling were acquired at the Ramsgate Harbour Approach Road tunnel in UK (Hiller *et al*, 2001). The tunnel was excavated using the 'prevault' tunnelling method, which uses a large chainsaw (Figure 2) to cut a series of slots in the ground. Each slot is then filled with sprayed concrete, before the next is cut. Thus, a full horseshoe-shaped lining is constructed before the bulk of the material within the tunnel is excavated.

Figure 2. Prevault tunnelling machine.

Vibration was measured on two occasions during different stages of this tunnel drive. The first set of data acquired at the Ramsgate tunnel plots below the rest of the chalk data. These data were for tunnelling in very weak, partially weathered, upper horizons of the chalk, immediately below the overlying superficial deposits (Brickearth; a homogenous structureless loam or silt), and with around 5m of cover between the tunnel crown and the foundations of the houses above.

The data marked 'more competent chalk' are vibration measured when the machine was tunnelling at a greater depth and excavating intact chalk. The data are consistent with the other chalk tunnelling data and therefore further support the hypothesis that it is the type of ground being excavated rather than the type or size of excavator that determines the vibration arising. The lower vibration from the weaker chalk also supports the hypothesis.

Rationalisation of the tunnelling vibration data

Intuitively it might be expected that a larger tunnelling machine would lead to higher vibration than a smaller machine working in the same ground. The data above indicate that this is not the case. It is thought that this is for the following reason.

The vibration is quantified in terms of the peak particle velocity (PPV), which is the highest velocity of an element of the ground (or building) that occurs during a vibration event.

During tunnelling, individual picks or cutters on the face of a TBM interact separately with the ground, such that at any instant, each tool will be in some various state of excavation – breaking the ground, moving previously dislodged material, passive, etc. The interaction of each of the tools with the ground and the consequential vibration caused at any instant in time will therefore differ for each tool.

The ground surface is the combination of the vibration from the actions of the different tools on the TBM with the ground. The amplitude, frequency and phase of the wave packet arriving at the ground surface from each tool will be different, so the peak vibration is not a summation of the peak vibration from each tool.

The PPV is therefore likely to be associated with interaction with the ground of only one individual tool on the cutter face, irrespective of the TBM diameter. Hence a bigger TBM does not create a higher PPV. Similarly, drilling holes with a percussive drill also requires attacking the ground at a single point and therefore vibration from these sources is similar to a TBM. The following considers whether this is also to case when quantifying vibration in terms of parameters other than the PPV.

In the UK, human response to vibration from sources other than blasting is assessed in terms of the vibration dose value (VDV; British Standards Institution, 2008). This approach sums all vibration exposure over the assessment period and is calculated from the fourth power of the frequency weighted acceleration. Quantifying vibration in terms of the VDV, or if assessments are based on the root mean squared acceleration or velocity, may not follow the same relationship as the PPV i.e. it may be that a larger diameter TBM would cause a higher vibration quantified as the rms or VDV because of the greater number of sources (picks or cutters on the face of the TBM) than a smaller source. Figure 3 presents calculated VDV data from three chalk tunnels excavated using a roadheader (Round Hill and Southwick sites) and a full face TBM (Channel Tunnel). The VDVs are calculated from intermittent measurements during excavation and then assuming that the sample VDV is continuous for the 16 hour period. The VDVs therefore provide an upper bound but standardised estimate of the true impact. The data do not show any clear difference in the VDV between the source types. This is an area requiring further research.

In terms of carrying out environmental impact assessments, as interesting implication of the PPV being determined by the ground being excavated is that there may be no means of reducing the impact from driving a tunnel in a particular location. The least intrusive method would therefore be the quickest, so that the duration of the impact is minimised. Confirming or otherwise whether the other parameters follow the same trend as the PPV would therefore be beneficial for future assessments.

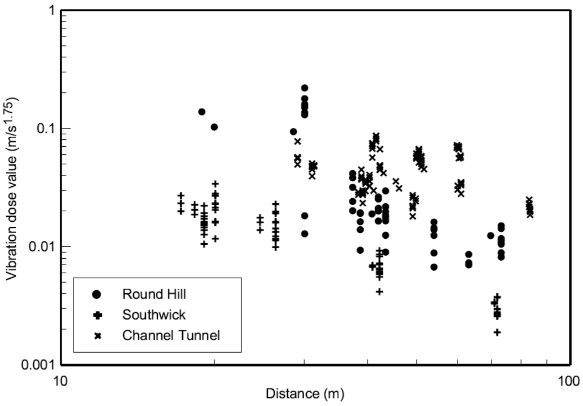

Figure 3. Calculated 16 hour VDV from tunnel boring (from Hiller and Crabb, 2000).

Drill and Blast

In some cases the most practical and economic option for excavation is drill and blast, even in urban environments. This is particularly likely to be the case for station openings, cross passages, escalator shafts, etc, constructed in hard rock. Methods for controlling blasting vibration are well established through the use of delays to limit instantaneous charge weights. Furthermore, the vibration from blasting is of short duration compared to other tunnelling methods, which might increase its acceptability.

However, each charged face will require blast holes to be drilled. This can take several hours to prepare each face and therefore potentially provides a more intrusive source than the blast itself. In particular, the effect of groundborne noise may be exacerbated due to the tonality of the noise caused by drilling.

Temporary Construction Railways

Temporary construction railways are generally the preferred option for transporting construction materials and personnel to the tunnel face and removing spoil, particularly for long tunnels. Characteristically, such railways are rigidly bolted to the tunnel invert and use jointed track. Track roughness is not a major consideration and poorly sprung vehicles with rough wheels can exacerbate vibration.

The temporary railway remains in place for the duration of the works, being extended as the tunnel is driven from the start to the end of the drive. They may therefore be operational and affecting noise/vibration sensitive receivers for many times longer than the duration for which the tunnel face passes and potentially present a more significant risk of complaint than the excavation phase.

There is little information available on the impacts of temporary railways. During construction of the London Tunnels for the UK High Speed 1 railway (formerly known as the Channel Tunnel Rail Link; CTRL), complaints arose from residents who could hear groundborne noise from the temporary railway. This heightened concerns, subsequently shown to be unfounded, that the operational railway would also be problematic.

Direct measurement of groundborne noise in properties could not be made, so vibration data were acquired during operation of the temporary construction railway, from which groundborne noise was calculated. The measured vibration data were within the range where the CTRL Prediction Methodology (Greer, 1999) would be valid. Table 1 presents the predicted groundborne noise for housing directly above the tunnel. It is interesting to note that the groundborne noise predictions did not decrease with increasing tunnel depth, possibly due to changes in geology.

Table 1. Groundborne noise calculated from vibration from a temporary construction railway

Tunnel depth (m)	Groundborne noise level dB$L_{Amax,S}$	
	Mean	**Maximum**
17.6	37	42
22.3	37	42
30.5	39	44
32.1	39	42

The predicted groundborne noise levels were consistent with the nature of comments received from residents living above the tunnelling works and are therefore considered reliable.

Prediction of the impacts from temporary railways is likely to require adaptation of procedures used for operational railways. However, many factors are outside the range of the parameters for which these procedures have been developed, such as the low speed, generally poor standard of track and wheels, rigid direct fixation to the tunnel lining. Further research in this area would be valuable to enable more robust predictions to be undertaken.

For London's Crossrail, onerous criteria have been set for groundborne noise from the temporary railway, which is required to achieve the same criteria as for the operational revenue trains. This is necessitating investigation of the use of alternatives, as the mitigation of vibration from a temporary railway to achieve the required levels is not practicable. Pneumatic tyred machinery is being considered as a solution to comply with the groundborne noise requirements.

IMPACTS AND CRITERIA

This section discusses current guidance on limits for groundborne noise and vibration. The range of vibration than can be significant is enormous: nanotechnology facilities may require a vibration climate defined by NIST criteria (see Amick *et al*, 2005) (~0.75×10^{-6}m/s rms), whereas building structures may be safe at a PPV of 50mm/s (British Standards Institution, 1993). Figure 4 compares criteria for the more sensitive situations.

Vibration measurement and monitoring

The range of criteria means that many proprietary monitoring systems are unable to monitor all situations. In particular, where very sensitive equipment is at risk, equipment designed for routine blasting or piling vibration monitoring may have too high a noise floor or insufficient resolution to measure the required vibration magnitudes. Instrumentation performance specifications must be matched with acceptability criteria.

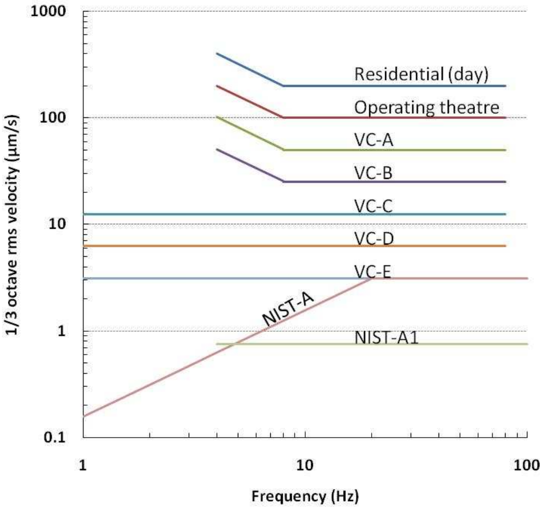

Figure 4. Vibration criteria for sensitive situations

In identifying vibration criteria, it is important to be clear and unambiguous in the definition of the measurement parameters. Criteria based on a limiting PPV are relatively straightforward. Where sensitive equipment is concerned, vibration criteria are often specified as the rms vibration velocity. Frequently, no further information is provided, that is required to quantify the rms, such as:

- is it an overall figure covering all frequencies (and defining the range of 'all frequencies'), or an octave or 1/3 octave or narrow band rms?
- over what duration should the measurement be determined?
- should a max-hold or time averaged rms be used?
- where should the vibration be quantified – eg on the floor, on the equipment?
- if the vibration is quantified on the floor, is it defined where the vibration is a maximum, or a spatial average?
- is the vibration defined as single (any?) axis or resultant?

These issues all significantly affect the assessed value of vibration. Therefore, without clear definition, it is not possible to carry out measurements that determine unequivocally whether the identified criteria are being exceeded.

For groundborne noise, criteria are often specified as the A-weighted maximum sound pressure level with a slow (1s) time constant. Table 2 presents groundborne noise criteria applicable to London's Crossrail.

The following sections describe briefly some examples of where receptor-specific criteria have been developed.

Vibration in Hospital Operating Theatres

During the planning stages of a new metro system in Dublin, Ireland, it was necessary to establish vibration limits for sensitive equipment and clinical processes for which none was available. In addition, during the initial tests, a surgeon questioned the established guidance on the magnitude of vibration acceptable in operating theatres during surgery performed under microscope.

Arup worked with Full Scale Dynamics Limited, a spin-off company of the University of Sheffield, UK, to determine when medical staff considered the vibration to be excessive.

This will be the subject of a separate paper; a brief summary is provided below.

Table 2: Construction* and operational groundborne noise criteria (from Crossrail, 2008)

Building	**Level dB $L_{Amax,S}$**
Residential buildings	40
Offices	40
Hotels	40
Theatres	25
Large auditoria/concert halls	25
Sound recording studios	30
Places of meeting for religious worship	35
Courts, lecture theatres	35
Small auditoria/halls	35
Schools, colleges	40
Hospitals, laboratories	40
Libraries	40

* Excluding groundborne noise from tunnel boring machines

Electrodynamic shakers were used to vibrate the floor while surgeons carried out simulated procedures or operated equipment. Additionally, standard set-up or calibration tests were carried out on some medical equipment to check whether vibration had any effect on its calibration or image quality.

Vibration was initially excited at discrete frequencies, but it became apparent that a better approach was to use random broadband excitation. Vibration was progressively increased in magnitude until medical staff reported that it would be a problem to procede, or a difficulty was identified with operation or calibration of the equipment.

While there were some limitations in the scope and experimental rigour of the tests, a lower limit of acceptable vibration of the theatre floor was established as 20µm/s (1/3 octave rms) for surgeons using microscopes. The microscope magnifications were set to those normally used by each surgeon and were typically x8 to x10 magnification. This appears to be onerous when compared with the Vibration Criteria curves (see ASHRAE, 2007 and Figure 4), which refer to microscopes with magnifications up to x400. It was also noted that vibration at the floor natural frequency was not the determining factor.

The reason for the sensitivity to relatively low vibration using low magnification microscopy was the amplification of the floor vibration by the cantilevered microscope stand (see Figure 5).

The 20µm/s criterion is more onerous than the Australian guidance given in AS 2670.2 (Standards Australia, 1990), which suggests 100µm/s (peak velocity) and UK National Health Services guidance document HTM 08-01 (Department of Health, 2008), which recommends a weighted acceleration of $0.005 m/s^2$ (rms averaged over 1s) which equates to approximately 100µm/s. In the US, the National Institutes of Health (2011) recommend a limit of 25µm/s for eye surgery, neurosurgery and ‘ordinary surgery’.

Table 3 provides a summary of the vibration limits determined by these tests.

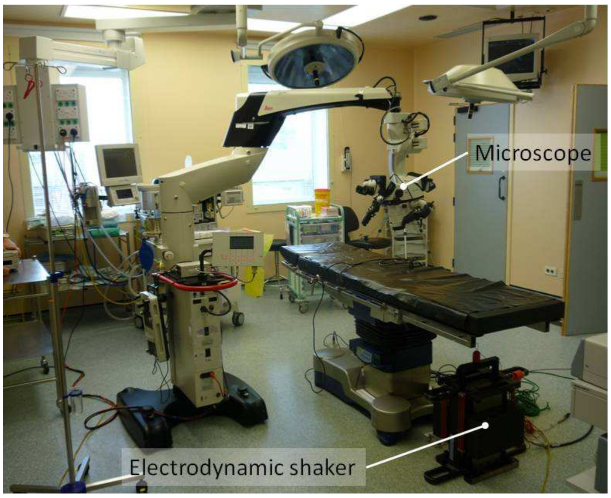

Figure 5. Experimental arrangement in operating theatre

Table 3. Experimentally determined vibration criteria

Equipment / process	**1/3 octave band rms velocity limit (µm/s)**
Operating theatre using surgical microscopy	20µm/s
Cardiac catheterisation laboratory	Defined by operator comfort – apply 100µm/s
Micromanipulator for artificial insemination	10µm/s
Gamma camera	Maximum excitation possible was 89µm/s. No visible degradation of image occurred at this velocity
Digital mammography	Maximum excitation possible was 51µm/s. No visible degradation of image occurred at this velocity

Groundborne Noise in Performing Arts Venues

Investigation by Arup in the early 1980s showed that at middle and high frequencies noise from trains should be limited to the same noise levels as the building services noise, i.e. the rail noise limit for a Preferred Noise Criteria (PNC)15 space should also be PNC15. At lower frequencies, however, where most rail groundborne noise occurs, the noise levels from the rail system can exceed PNC15.

Arup therefore developed a rail noise limit for the design of critical music and drama auditoria as shown in Figure 6. This criterion would be equally applicable to temporary construction railways, where a performing arts space is affected over an extended length of time.

The rail noise criterion set out in Figure 5 does not equate to a single overall level. However, for commonly experienced train noise spectra, when expressed as an overall maximum noise level, the criterion is not significantly different to a $25dBL_{Amax,slow}$ criterion, which therefore remains relevant for prediction assessments.

Damage to existing subsurface infrastructure

Strathclyde Partnership for Transport (SPT), the operator of the metro system in Glasgow, UK, has recently commissioned work to establish a protocol to ensure that construction works in the vicinity of SPT’s tunnels will not risk causing damage to the existing tunnels, but will not unduly restrict nearby construction works. These criteria are applicable to all works, whether ground surface or tunnelling and were developed to improve upon the previously applied blanket requirement that a PPV of 2.7mm/s must not be exceeded at a tunnel lining.

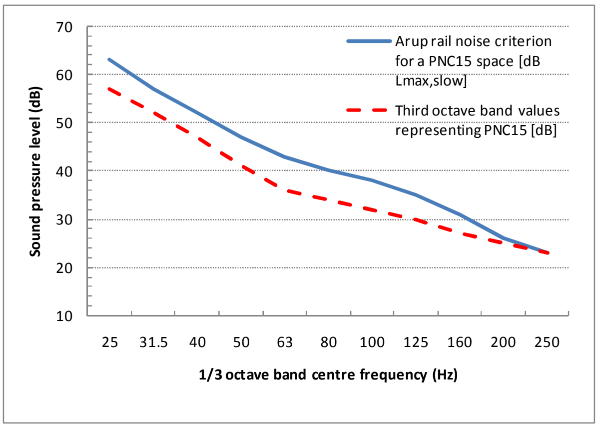

Figure 6. Groundborne noise criterion for a PNC15space

The Glasgow tunnels were constructed using several different techniques and therefore different criteria apply, depending on the type of lining. The criteria were developed from a literature review and a series of measurements to quantify the existing vibration from trains, to ensure limits were not set below the vibration to which the linings are routinely exposed.

A 'traffic light' system has been developed (see Table 4). This requires contractors to carry out predictions of vibration from their proposed works and compare the predictions with the criteria to define the required course of action. The consequences of any damage to the operational tunnels are large. The criteria have therefore been established at levels that are considered to be conservative, but which should provide some flexibility to developers in the vicinity of the subway.

Table 4. PPV criteria (mm/s) and associated actions for transient or intermittent** vibration

Action required	**Tunnel lining**		
	Brick or mass concrete in poor* condition	**Brick or mass concrete in good* condition**	**Cast iron, steel or concrete segmental lining**
Proceed using only the construction methods for which calculations have been approved by tunnel operator. In-tunnel monitoring not required – at tunnel operator's discretion	<3	<6.5	<7.5
Works may proceed. Continuous alarmed monitoring in tunnel will be required in all cases	3 – 6	6.5 – 12.5	7.5 – 15
Alternative construction methods required	>6	>12.5	>15

* Condition of the tunnel in this context to be determined and specified by the tunnel operator.
**PPVs should be reduced by 50% for continuous vibration.

During construction, vibration will be monitored in the cases described in Table 4. If measured PPVs reach the relevant 'red' criterion, the contractor is required immediately to stop the works. The source of the vibration that attained the red trigger is to be determined and, if it is confirmed to be the construction process, an alternative will be required.

The 'amber' levels can be used to set up alert text messaging that alerts all parties to the fact that the vibration is approaching the allowed limit. The contractor will then be aware that the methods could be problemmatic and have contingencies in place should the 'red' be reached.

Vibration damage of concrete

In major infrastructure works, there is often a desire to be able to carry out heavy excavation, including blasting, in the vicinity of recently constructed elements of the same project. There may be programme benefits in constructing cast *in situ* tunnel linings as close as possible to the face excavation. The question therefore arises: how close to blasting can concrete be placed without risk of compromising the integrity of the structure? A similar situation could arise for top down construction, where the integrity of structural concrete needs to be maintained while excavation continues beneath.

When specifying criteria and monitoring vibration in the vicinity of green concrete, it is important to distinguish between structural elements (for example, a suspended roof slab in a top-down station box construction) and mass concrete placed directly in contact with the ground. For the former, damage criteria applied to buildings would apply once the concrete has cured, but a lower limit would be required during curing, if full strength has not been reached.

For mass concrete, New, 1992 reported on tests on vibration between 11 and 45 hours old. In these tests, vibration was measured directly on the test specimen as a PPV and also as a direct measurement of strain within the specimen, using buried strain gauges. Across the whole age range, the failure occurred at a dynamic strain that was independent of age of the specimen and was in the range 70 to 130 micro-strain. The PPV at failure was calculated from knowledge of Poisson's ratio and the wave velocity and was found to increase with age to around 200mm/s.

Ansell (2004) carried out blasting tests close to recently sprayed unreinforced shotcrete, with ages from 1 to 25 hours. It was concluded that young shotcrete (up to a day old) can withstand extremely high vibration, the main failure mechanism being loss of adhesion with the rock. This typically happened at between 500 and 1000mm/s PPV.

Tests similar to those conducted by New, but much more extensive, were reported by Kwan and Lee, 1998. The lowest bound PPVs that may cause damage are presented in Table 5 and are comparable with the assessment given by New. Kwan and Lee suggested that these values should be divided by 5 to provide an assessment criterion; this may be seen as unduly restrictive.

The PPVs in Table 5 refer to mass concrete. Structures are less resistant to damage. Current guidance in the UK (British Standards Institution, 1993) is among the least onerous globally, stating that for "reinforced or framed structures – industrial or heavy commercial buildings" the limit is 50mm/s. During curing, particularly while concrete is very weak, structural elements should be treated more cautiously, since the tensile strength will be reduced by minor cracking. Kwan and Lee demonstrated that such cracks cannot be relied upon to self-heal.

Table 5. Vibration damage criteria for mass concrete

Age (hours)	Lower bound PPV limit (mm/s)	Age (days)	Lower bound PPV limit (mm/s)
2	46	0.5	250
4	52	1	350
6	130	3	500
8	180	7	690
10	170	28	750

Screening Distances

In assessing the risks due to a tunnelling project, it is beneficial to be able to define a corridor outside of which it is not necessary to undertake vibration assessments. The US Federal Transit Administration (FTA; 2006) provides guidance on screening distances for operational railways, but similar screening information is not available for construction works.

A particular difficulty is that there are insufficient data available with which to make validated predictions to the distances required for screening out the most vibration sensitive receivers (e.g. medical facilities and nanotechnology laboratories). Those predictors that are available would require extrapolation well beyond the distance for which the predictors are applicable. In addition, there are practical and financial implications to defining an extensive screening corridor because of the potentially very large number of buildings that would be encompassed in an urban area and which would therefore need to be reviewed.

For temporary construction railways, screening distances applied to conventional operational railways such as those given by FTA may be appropriate. The FTA screening distances range from 120 to 600 feet (approximately 35 to 180m) for “conventional commuter railroads” and depending on the sensitivity of the receiver.

Based on practical experience, a corridor width of 200 to 250m is appropriate in urban environments. In rural locations, a wider corridor may be required, due to the potentially lower levels of ambient vibration and noise. The implications of a wider corridor in rural areas are offset by the lower density of buildings.

During a scoping exercise, where new tunnelling works are proposed in the vicinity of existing infrastructure, particularly railways, it may be reasonable to assume that any very sensitive installations have already been designed to accommodate vibration, perhaps through antivibration mounts. However, the design of the existing infrastructure would need to be checked to determine whether mitigation has been installed at source, such as through resilient rail mountings.

MITIGATION

This section outlines options for reducing the effects of groundborne vibration during tunnel construction works.

Change of Tunnelling Methods

As described earlier, it is the ground being excavated, more than any other variable, that determines the PPV during tunnel excavation. Consequently, there are no practicable means of reducing the PPV during the excavation phase. It has been suggested that reducing the cutter head speed of a TBM, or reducing the thrust on the face may reduce vibration, but no data are available in support of this. Furthermore, considerations other than vibration are likely to limit the amount by which any such approach would be possible.

An alternative may be to restrict working hours. A balance needs to be struck between 24 hour working, which may lead to night time disturbance, and working only during the day, which would prolong the works. Generally it is considerably safer and more efficient for tunnelling to continue uninterrupted.

Route Alignment

Changes to the route alignment can lead to benefits if it is possible to move the tunnel or associated infrastructure (ventilation shafts, station openings, etc) away from the most sensitive receivers. However, sometimes the occupants of the affected buildings will benefit from the operational tunnel being close at hand, and the longer term benefits may outweigh the temporary adverse impacts during construction.

Changing the route alignment so that the tunnel is driven through a softer material would reduce vibration, but this is unlikely to be practicable in most cases once a route corridor has been selected. Increasing the distance between the tunnel and sensitive receivers needs to give due consideration to any changes to the type of ground that may result. Increasing the tunnel depth may move the tunnel into a harder stratum, leading to an increase in vibration, despite the greater distance.

Public Relations and Consultations

Where disturbance to the occupants of dwellings is the principal concern, the most successful mitigation approach during tunnel excavation is likely to be through consultation and good public relations. Most commonly, residents are concerned that vibration will damage property. These concerns can often be suceesfully addressed by engaging with the public, explaining the large difference between perceptible and damaging vibration, and through open, visible and possibly independent monitoring. During construction of the Ramsgate tunnel, many concerned residents were placated by knowing that an independent organisation, not involved with the construction, was measuring vibration in and around some of the closest houses to the works.

For other vibration sensitive receptors, mitigation may be more problematic as disturbance is not due to subjective perception but physical interaction with equipment or processes. For example, hospitals using vibration sensitive equipment may not be able to interrupt or relocate their facilities and a compromise may need to be reached, such as restricting construction works to weekends only, or temporary relocation.

Temporary Construction Railways

Vibration and groundborne noise from a temporary construction railway may be reduced through similar means as permanent railways are treated, such as by welding and smoothing joints; and regular inspection and maintenance of track and rolling stock to maintain smooth running systems. Such interventions may not be practicable and may be difficult to implement in practice.

Resilient mounting of the track may be feasible, but it will need to be ensured that the safety implications of introducing resilience, particularly laterally, need to be assessed.

Vibration from railways generally increases with increasing speed, so there is likely to be some benefit in slowing supply trains along critical sections of the track. Measurements made during construction of High Speed 1 showed a 5dB reduction in groundborne noise for a reduction from 15 to 10km/h.

A further option may be to install a conveyor system to remove spoil. This would reduce the number of train movements required, but vehicles of some type would still be required to import construction materials (especially lining segments) and personnel. Pneumatic tyred vehicles may be a possible alternative to a railway, which would eliminate vibration impacts.

CONCLUSIONS

This paper has presented a summary of the latest assessment criteria assessment and mitigation from tunnel construction vibration and groundborne noise. While there has been and continues to be a great deal of study of the impacts of operational railways in tunnels, significantly less research has been applied to the temporary impacts caused during construction.

While many of the impacts associated with construction are of relatively short duration, their effect on sensitive receivers can be significant and therefore a better understanding of the impacts, robust assessment and viable mitigation options are important when planning subsurface infrastructure. It is hoped that the information provided in this paper will enable more informed assessments to be made. A number of areas requiring further research have been identified, which would further take forward the industry's capabilities in this area.

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