MANAGING EFFECTS FROM GROUND-BORNE NOISE AND VIBRATION DURING CONSTRUCTION OF THE HS2 CHILTERN TUNNELS, BEING DELIVERED BY ALIGN JV.

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1 INTRODUCTION

Phase 1 of the High Speed Two (HS2) railway line currently being constructed between London and Birmingham will pass below the Chiltern Hills in Buckinghamshire, United Kingdom through twin-bore parallel running tunnels each approximately 16 km in length and 8.8 m in diameter. Figure 1 presents an overview of the tunnel route in this section, passing beneath several residential communities including Chalfont St Giles and Amersham.

The main works civils contractor responsible for the construction of the tunnels is Align (a joint venture between Bouygues Travaux Publics, Sir Robert McAlpine and VolkerFitzpatrick). Southdowns Environmental Consultants Ltd (RWDI) was retained to provide specialist advice on groundborne noise and vibration risks to the Align JV. The construction of the Chiltern Tunnels requires the use of two tunnel boring machines (TBMs), excavating through geology that comprises a mix of clay, chalk and flint, and the hydraulic breaking of both concrete and geological faces to excavate a series cross passage tunnels. These construction activities occur on a 24 hr basis, passing beneath several residential and commercial properties along the route at depths ranging between approximately 20 m to 90 m beneath overlying buildings.

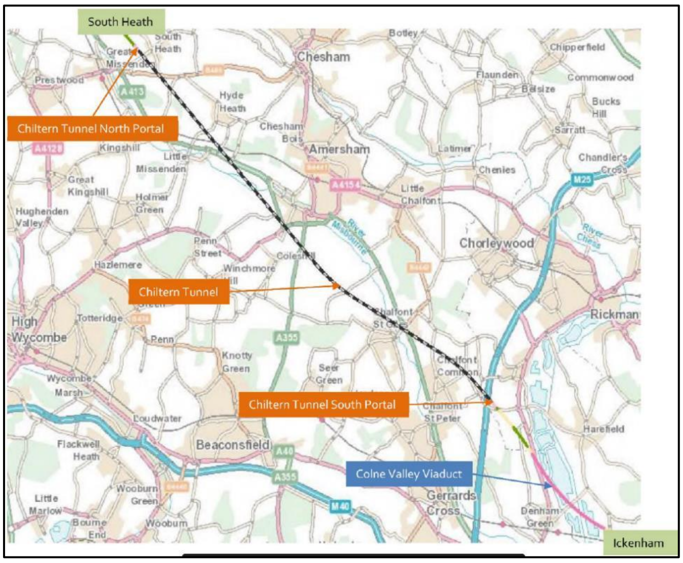

Figure 1 Overview of HS2 Chilterns Tunnels Route.

The excavation methods adopted for the construction of the Chilterns Tunnels have potential to give rise to adverse groundborne noise and vibration (GBN&V) effects inside properties overlying the tunnel trace. Key GBN&V challenges that have been faced along the route include the construction of the tunnels below sensitive receptors such as hospitals, listed historical buildings, and occupied properties within residential communities.

To manage the effects of GBN&V on the communities and sensitive receptors overlying the Chilterns Tunnels route, a staged process has been implemented:

- Initial scoping risk assessment of GBN&V using established simplified prediction methods;
- Detailed assessment of GBN&V using numerical modelling;
- Investigation of GBN&V through a series of attended and unattended measurements;
- Model refinement and updated predictions of GBN&V based on measured data.

At each stage in the process the findings of the investigation were fed back to the community engagement and construction teams, to ensure continuity in the management and monitoring of the effects of GBN&V during the construction of the tunnels.

2 TUNNELLING ACTIVITIES

2.1 Tunnel Boring Machine

The twin-bore tunnels are currently being excavated using two TBMs (named Florence and Cecilia) that were launched in 2021 in a staggered programme and operate continuously in a northward direction, with their arrival at the north portal expected in spring 2024. Each TBM consists of a rotating disc cutter head which bores into the rock/soil being tunnelled through, as shown in Figure 2. Behind the disc cutter is a shield and supporting equipment which includes a pressure chamber, a conveyor belt, slurry pipelines and hydraulic jacks. The TBMs were specially designed to operate as a slurry type boring operation and/or an earth pressure balance system, allowing the TBM to adapt to the stiffness of the geology being bored through.

The vibration generated by a TBM is typically continuous in nature but can vary in magnitude depending upon the rotational speed of the disc cutters, the type of TBM operation, the lithology being bored through, the thickness and the density of the overlying ground and the excavation rate required. The primary influence on the magnitude of vibration generated by the TBM at source is the amount of energy required to bore through the rock or soil at the required production rate[1].

Figure 2 Example of the TBM used on the project, prior to launch.

During operation cycles, the TBM is temporarily ceased to allow for the installation of incremental segment concrete rings behind the cutter head that form the primary lining. The installation of a segment ring typically lasts about 30 minutes. Once the segmental ring has been installed, the TBM re-starts for the next cycle of excavation. The TBM continually operates on a 24 hr basis, and advances on average at a rate of 15 to 30 m per day, including phases of excavation, ring installation, maintenance and operative shift changeover at the TBM.

2.2 Hydraulic Breaking

In addition to the main tunnel bores, 38 no. Cross Passages (CPs) are to be constructed between the tunnels at approximately 500 m intervals along the tunnelled section, to provide emergency and maintenance access once operational. The CPs are of a smaller diameter than the main tunnel bores and are constructed using the Sprayed Concrete Lining (SCL) technique shown in **Error! Reference source not found.**. overleaf

SCL involves the use of hydraulic breakers and more traditional excavation techniques to create the passageways. The construction methodology of each CP consists of removal of the primary lining (concrete segments) of the main tunnel drives, gradual excavation of the rock/soil in 1 m increments, spraying of concrete (shotcrete) onto the exposed surfaces, rapid curing of the concrete, breaking of the cured concrete lining, and the continued excavation of rock/soil in the next 1 m increment.

The use of hydraulic breakers has been required for the removal of the primary lining, sprayed concrete linings, and stiff rock faces such as competent chalk and flint. The CP construction works take place on a 24 hr basis, and typically last for up to two weeks at each cross passage location.

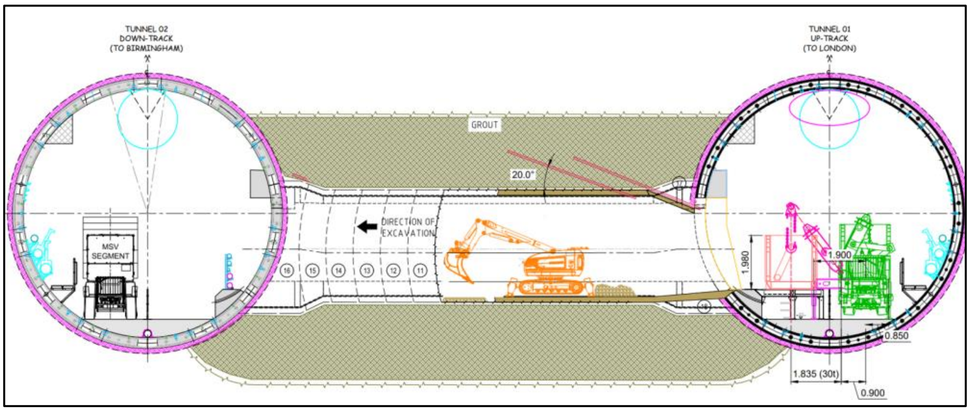

Figure 3 Schematic diagram of cross passage excavation works between main twin bore tunnels.

3 GROUNDBORNE NOISE AND VIBRATION

The groundborne vibration associated with the TBM and hydraulic breaking activities can be described as periodic and deterministic, meaning that the level of vibration induced in the subsurface can be predicted.

The magnitude of groundborne vibration naturally decays with distance due to the geometric spreading of the wave motion, and due to the effects of the damping characteristics of the media through which the vibration is propagating, inhomogeneity in the layers of the media, anisotropy and the influence of confining pressure on the dynamic moduli of the ground media. Due to a preferential attenuation of higher frequencies through typical soil media, groundborne vibration generally occurs between 0.1 to 315 Hz.

Vibration can be described in various ways. Typically, the peak particle velocity (PPV)[2,3] is widely used for the assessment of vibration on structures, utilities and other sensitive equipment (including computers and laboratory equipment), as well as for the assessment of human subjective response to demolition and construction related vibration. In the UK, the Vibration Dose Value (VDV)[4,3], expressed in $ms^{-1.75}$, is also widely been used for the assessment of human vibration exposure.

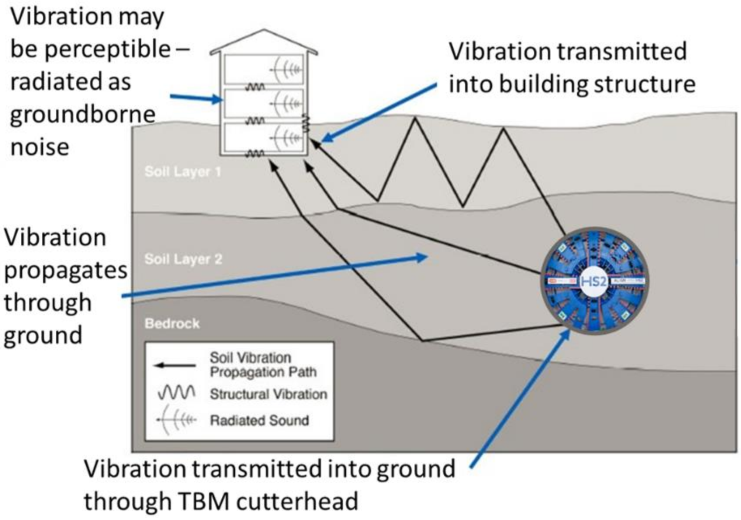

Figure 4 Example of the propagation of vibration energy from the TBM cutterhead to a receptor at surface

Whereas an assessment concerned with the potential for building damage risk would consider vibration magnitudes at the foundation and external to the building, an assessment of human response to vibration is based upon the magnitude and duration of vibration at the point of entry to the human body. This requires consideration of how the vibration propagates from an external position to an internal position and which is near to the centre of the floor in the room being considered.

Groundborne noise refers to the unwanted sound generated inside buildings due to vibrations in the ground which cause building surfaces such as walls, floors and ceilings, to vibrate and radiate sound within a room. The presence of groundborne noise inside a building can give rise to concerns from building occupants about building damage as well as to potential disturbance or annoyance. Subjectively, groundborne noise due to TBM operation is often described as a low frequency 'rumbling' sound, with the audible sound pressure energy typically occurring in frequencies from around 25 to 315 Hz. The noise indicator commonly used to assess groundborne noise is L_{pASmax}. This indicator is the maximum A-weighted sound pressure level measured with the SLOW time weighting applied. Use of this indicator originates from its use in assessing GBN&V from trains operating in tunnels where discrete events occur.

The use of the hydraulic breakers within the cross passages is a percussive source of vibration and when SCL works take place on 24hr basis, have potential to give rise to GBN&V disturbance in buildings overlying the works. Typically, the same indicators are used to assess the effects of GBN&V from this activity.

In general, it is not practicable to mitigate the temporary effects of construction GBN&V using control measures at (or within) the building. Options for controlling vibration generation from TBMs are limited given the safety critical need to tunnel continuously to minimise the risk of any issues relating to ground instability. Some options are available to control vibration caused during CP construction by re-arranging working patterns or methodologies for certain equipment uses. Where no other options are available for controlling significant adverse effects from GBN&V, then temporarily re-locating occupants may need to be considered.

4 ASSESSMENT CRITERIA

The project's commitments in relation to construction GBN&V effects are set out in the HS2 Code of Construction Practice (CoCP)[5] and in HS2 Information Paper E23 Control of construction noise and vibration (IP E23)[6] and are summarised below.

Assessment Type	**Human Disturbance**			**Building Damage**	
	LOAEL	**Impact Threshold Criterion**	**SOAEL**	**Screening Criterion Residential**	**Screening Criterion Commercial**
Groundborne Noise	35 dB L_{pASmax}	-	45 dB L_{pASmax}	-	-
Groundborne Vibration	Daytime 0.2 $ms^{-1.75}$ VDV Night-Time 0.1 $ms^{-1.75}$ VDV	Daytime 0.4 $ms^{-1.75}$ VDV Night-Time 0.2 $ms^{-1.75}$ VDV	Daytime 0.8 $ms^{-1.75}$ VDV Night-Time 0.4 $ms^{-1.75}$ VDV	1.0 mms^{-1} PPV	3.0 mms^{-1} PPV

Notes:
[1] The groundborne noise thresholds for human disturbance are applicable to levels measured inside a property occurring at any time;
[2] The groundborne vibration thresholds for human disturbance adopted by the project are applicable to the 16 hour daytime (07:00 to 23:00 hrs) and 8 hour night-time (23:00 – 07:00 hrs) periods;
[3] For the purposes of this assessment, the daytime VDV thresholds have been applied to the ground floor of any building and night-time VDV thresholds to the first floor (or above) of residential buildings to represent a bedroom.

The project's commitments require that all reasonable steps are taken so that noise and vibration from the construction of the scheme does not exceed the LOAEL. Where it is not reasonably practicable to achieve this objective then noise and vibration will be reduced as far as is reasonably practicable. Where noise and vibration from the construction exceeds SOAEL, then additional off-site mitigation will be offered with the aim that noise and vibration from construction does not give rise to significant adverse effects on health and quality of life. In the case of construction GBN&V, the SOAEL threshold is used as the basis for screening residential properties that might require further consideration for additional mitigation on a case-by-case basis under the ‘Special Case’ provisions (App A para 6 of Information Paper E23)[6]. This screening is subject to a temporal criterion of two or more consecutive days of exposure to ground-borne noise or vibration.

In addition, the CoCP requires that Best Practicable Means (BPM) (as defined in Section 72 of the Control of Pollution Act 1974) will be used to control vibration so that certain thresholds are not exceeded. In the case of human disturbance the vibration thresholds should not be *routinely* exceeded (considered to be 10 days in any 15 consecutive days). Building damage screening thresholds are applied in the CoCP for triggering the need for more detailed assessments.

5 SCOPING STUDY

A scoping study was undertaken prior to construction, to assess the need for further, more detailed, studies at specific areas where receptors might be adversely affected, and to provide an early indication of the footprint of the requirement for GBN&V specific community engagement. The scoping study adopted the prediction algorithms published in BS 5228-2:2009+A1:2014[2] for GBN&V from TBM operation[7], and formulae empirically derived by Southdowns during work relating to the construction of Crossrail platform tunnels[8] in Whitechapel and Liverpool Street Stations, using the SCL method.

The scoping study used precautionary worse case assumptions of geological conditions, temporal exposure to vibration sources based on typical progression rates of the TBM and hydraulic breaking activities, and the transfer of energy to building elements. The results of the scoping study highlighted that estimations of daytime and night-time VDVs provided the largest SOAEL footprint and highest building counts, particularly for night-time. The outputs from the scoping study provided initial information on where advance community engagement would be necessary. The results also provided a first pass on the potential quantity of properties requiring consideration as Special Cases, and potentially requiring temporary re-housing assuming at least 2 days of exposure.

An initial set of GBNV surveys at the first cluster of properties above the TBM at a depth of c.40m had indicated that the scoping studies were fit for purpose.

The scoping study stimulated a number of early community engagement initiatives, aimed at identifying and informing occupants of buildings potentially expected to experience perceptible magnitudes of groundborne noise and/or vibration during the tunnelling works.

6 DETAILED ASSESSMENT

The scoping study identified a number of risks and limitations and recommended that further more detailed studies be conducted to reduce the uncertainty in the prediction methodology and the cautious assumptions applied for the scoping study.

The vibration modelling of the TBM and SCL activity has been undertaken using FINDWAVE®, a finite difference time-domain numerical modelling programme for computing the propagation of waves in elastic media resulting from the excitation from sources of vibration, such as subsurface railways and tunnel boring activities. FINDWAVE® has been applied previously for the calculation of GBN&V from TBM activity on other major tunnelling projects including: Crossrail[9], Dublin Port Tunnel; Silvertown Tunnel; Lower Thames Crossing; and the Cross Island Line in Singapore.

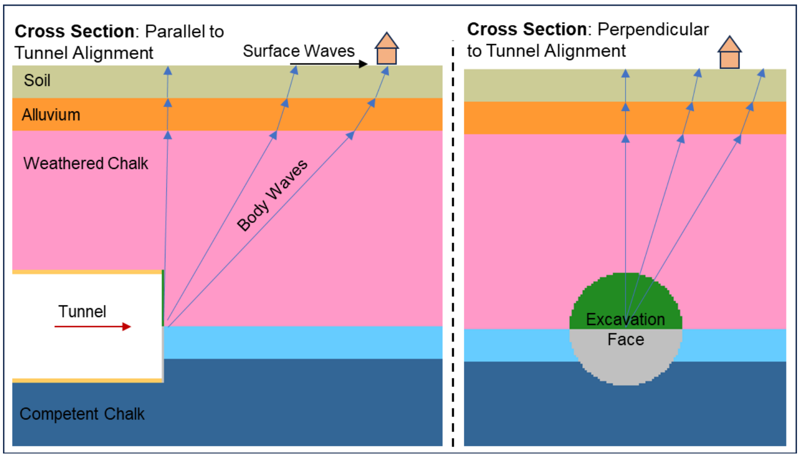

Figure 5 Modelling of vibration propagation using FINDWAVE®

A number of 3D models were developed over the geographical areas of interest, including the Chalfont St Giles community which features the shallowest tunnel depth (20 m), and at Amersham Hospital. The models featured different tunnel depths and geophysical properties of the rock and soil layers, derived from the geotechnical information available along the Chilterns Tunnels route. RIVAS[10] building transfer functions were adopted to model the transfer of vibration energy from a free-field surface environment to the internal building environment.

From a review of published information and other information available from contemporary tunnelling projects including Crossrail, vibration data were obtained and used for the derivation of a source-term for the HS2 TBMs. The source-term was adjusted to account for the thrust pressure, rotational speed and cutter head size of the HS2 TBMs to derive to representative source-term for modelling the HS2 TBM. For the construction of the CPs, the source term associated with the hydraulic breaker was derived from field measurements from a similar sized hydraulic breaker in operation at the surface. All calculations included a +5 dB adjustment to account for model and assumption uncertainty commensurate with the requirement to proceed with the study in a cautious fashion.

The results of the FINDWAVE® modelling of TBM operation found that the number of exceedances of the groundborne vibration LOAEL and SOAEL thresholds were significantly reduced compared to those calculated in the scoping study, providing a reduction in the number of properties potentially affected by groundborne vibration.

In contrast, the calculated groundborne noise levels calculated using FINDWAVE® were up to +2 dB higher than the groundborne noise levels calculated using the BS 5228-2 empirical predictor. The levels predicted using FINDWAVE® include the +5 dB correction for potential model uncertainty.

The above findings therefore suggested that groundborne noise was likely to affect more properties than groundborne vibration. This observation enabled the community engagement activities to be geared more towards communications centred around the risk of noise effects, rather than vibration effects.

Groundborne noise SOAEL exceedances were predicted at 40 properties, of which 34 were residential buildings and 6 were non-residential. The duration of the exposure to noise levels of this order was anticipated to be up to 3 days based on 15 m per 24 hrs progression.

The results of the numerical modelling of CP construction indicated that there were no groundborne noise or vibration LOAEL or SOAEL exceedances predicted at receptors, and therefore no properties forecast to be considered as 'Special Cases' as a result of the Cross Passages' construction.

7 COMMUNITY ENGAGEMENT

The Align JV Community Engagement team developed their initial communications strategy using the findings from the detailed assessment, having established that groundborne noise was a greater risk than groundborne vibration. Figure 6 presents contour information from the detailed assessment used to identify key stakeholders.

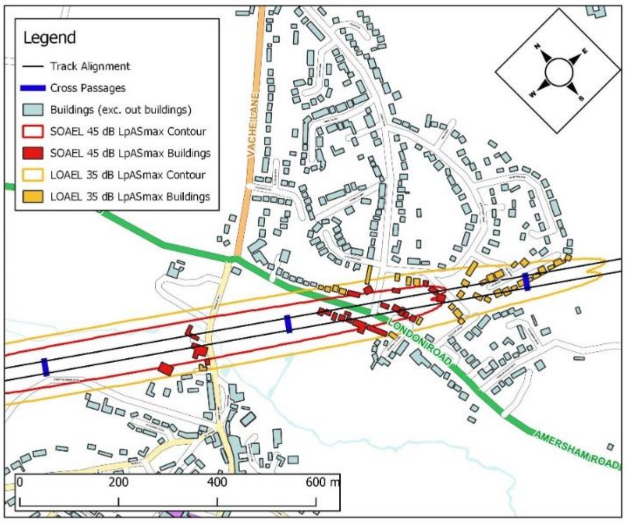

Figure 6 Groundborne noise contours due to TBM operation produced from numerical modelling.

Given the limitation on other practicable mitigation measures for tunnel construction works, the strategy was considered to be a key element of managing people's responses and expectations during the works, and the communications included presentations to the Local and Parish Councils of the worst affected communities.

Specific in-person doorstep discussions and letter drops were undertaken for all properties predicted to exceed LOAEL, with information on the works, what GBN&V is and what to expect, when to expect it and for how long. The communications also targeted residents expected to experience the higher magnitudes of GBN&V above SOAEL and included information about temporary respite measures for those opting to move out of their homes during the anticipated worst phases of works. The detailed assessment results enabled a number of risk management activities to commence, including the block booking of hotel accommodation for the proportion of occupants expected to opt for temporary respite.

Those opting for temporary respite provisions were consulted regularly on the likely dates of the worst effects and re-location arrangements with the building occupants made in advance of the TBM approaching the community. In a number of cases the residents vacating their properties also agreed to the stationing of noise and vibration monitoring equipment within their property to enable Align JV to gather vital measurement information during the passby of the TBMs.

8 MEASURED GBN&V DATA

A series of groundborne noise and vibration surveys were undertaken at the earliest opportunities along the tunnel trace, to provide measured data from which to re-calibrate the vibration source term adopted in the numerical models and to inform and update the community engagement strategy, where necessary.

8.1 Tunnel Boring Machine Monitoring

The surveys of TBM operation included groundborne vibration monitoring at 1 no. free-field location and at 6 no. residential properties, of which 4 no. surveys included groundborne noise monitoring. The residential properties were all 2-storey buildings directly overlying the tunnel trace, with varying constructions that included a late 20th century property, a modern converted property, and a grade II listed barn conversion. The tunnel depth beneath the buildings surveyed ranged from approximately 50 m to 20 m between the tunnel crown and the local ground at surface.

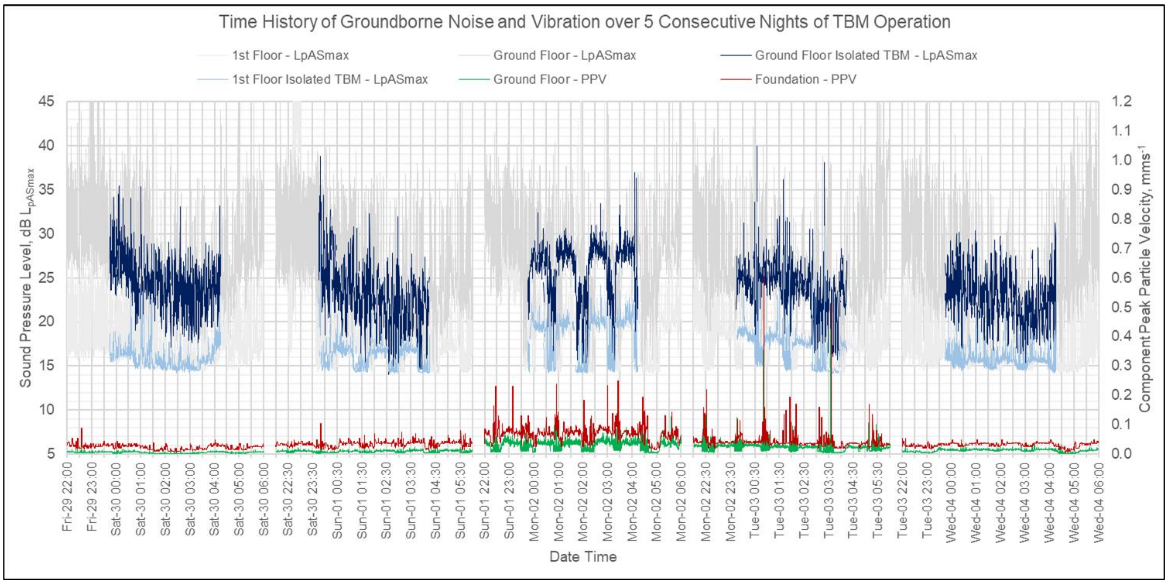

Figure 7 Example time history of groundborne noise and vibration data during TBM operation

The surveys included attended and unattended measurements at free-field, foundation, ground floor and 1st floor locations during the passage of the TBMs, in buildings that were either occupied or unoccupied. Due to the influence of ambient and extraneous noise or vibration sources such as road traffic or passing aircrafts, or internal resident activity such as footfall and closing doors, the analysis of the GBN&V data focussed on night time periods to take advantage of the lower levels of ambient and extraneous noise and vibration sources. In some cases, vacant buildings were available for the surveys to improve the data capture quality.

The periods of TBM operation could be identified through detailed analysis of simultaneous groundborne noise and vibration data in both the time and frequency domains, as indicated on **Error! Reference source not found.** where the night-time measurements are highlighted, and in which the energy associated with TBM activity was contained in the 25 Hz to 200 Hz third-octave frequency bands. This figure also highlights the cyclical nature of TBM operation, switching between phases of TBM excavation (typically occurring for 1 hr) and segment ring installation (typically occurring for 45 mins). The progression of the TBM can also be identified based on the gradual rise and fall of GBN&V data over the 5 day period, which features the highest levels associated with the TBM drive on the 3rd night, and the highest levels associated with ring installations (12 m behind the TBM cutterhead) on the 4th night.

The highest groundborne noise levels attributed to the operation of the TBM during tunnel drives were up to 41 dB L_{pASmax} but these noise levels were isolated, untypical and infrequent events. Statistical analysis of the data associated with TBM operation provided a useful means of extracting an upper bound region of the continuous GBN&V level produced by the TBM, represented by the top 5th percentile level which ranged between 19 and 34 dB L_{pASmax} depending upon the night considered. The application of the top 5th percentile level also helped to reduce the influence of potential extraneous noise sources that might have remained in the data after post processing. This statistical percentile approach was considered to yield a more suitable measure for the assessment of human disturbance, and more relevant for the protection against the onset of adverse effects on quality life and wellbeing from a relatively continuous source. Groundborne noise levels associated with segmental ring installations were measured up to 40 dB L_{pASmax} and were impulsive in nature, occurring up to 7 times per segment installation and in some instances produced GBN&V levels higher than the corresponding adjacent TBM excavation phases themselves.

There were no measured individual exceedances of the 45 dB L_{pASmax} SOAEL threshold due to TBM operation, and only 3 no. measured individual exceedances of the 35 dB L_{pASmax} LOAEL threshold. The measured groundborne noise level was typically 8 to 10 dB below the corresponding predicted groundborne noise level calculated using FINDWAVE® (which included a +5 dB allowance for model uncertainty).

The PPV magnitudes were measured to be up to 0.65 mms^{-1} during a TBM drive and up to 0.61 mms^{-1} during ring installation activity. Measured free-field PPV values attributed to the TBM activity were comparable with the numerically modelled predictions.

Internal VDVs calculated over a 16 hour daytime and 8 hour night-time periods fell significantly below the LOAEL thresholds of 0.2 $ms^{-1.75}$ for the daytime and 0.1 $ms^{-1.75}$ for the night-time assessment periods presented in HS2 Information Paper E23, and were significantly lower than the highest predicted VDVs, which were up to 0.4 $ms^{-1.75}$.

With the +5 dB allowance for uncertainty removed, the comparison of the measured and predicted groundborne noise indicates that the RIVAS building transfer functions (used to convert groundborne vibration from an external free-field position to a floor position inside a building) are reasonably precautionary for the building construction types included in the surveys, contributing to the remaining c. 3 to 5 dB headroom that appears to be evident in the L_{pASmax} predictions. It was considered important that this level of headroom was maintained for these types of risk assessment studies so that a full range of potential different building types and construction are taken into account, especially where details on individual buildings are not known. As a result, no further adjustments to the direct application of the RIVAS transfer functions were deemed appropriate.

The significant reduction in measured VDV compared to the numerical predictions highlights the uncertainty in the methodology used at the scoping stage which assumed a continuous PPV could be maintained over the entire assessment period. In practice, the surveys have shown that a lower and fluctuating vibration signal is associated with TBM activity over discrete portions of the daytime or night-time period, resulting in a significantly lower VDV.

8.2 Cross Passage Monitoring

Groundborne noise and vibration monitoring during the hydraulic breaking activity associated with the construction of HS2 cross passage tunnels was undertaken at 1 no. free-field location 40 m above a CP tunnel and 1 no. residential property 55 m above a CP tunnel. The excavation works included the use of a BROKK hydraulic breaker for the breakout of the concrete primary lining tunnel segments, temporary sprayed concrete lining surfaces, and the excavation of chalk material.

At 55 m from the CP tunnel, internal groundborne noise levels attributed to the hydraulic breaking were up to 41 dB L_{pASmax}, and exceeded the 35 dB L_{pASmax} LOAEL threshold on a number of consecutive days. The groundborne noise was audible, and could be characterised by a high contribution of impulsive energy contained in the 31.5 Hz and 125 Hz third-octave band frequencies, as indicated in **Error! Reference source not found.**.

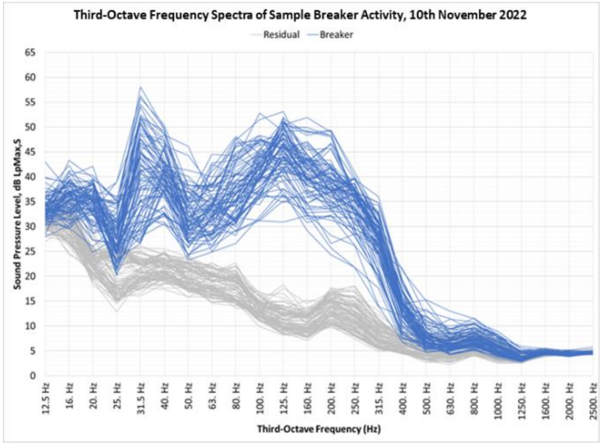

Figure 8 Third-octave frequency spectra of hydraulic breaking activity measured inside a residential property.

The peak particle velocity magnitudes attributed to the CP excavation activity were up to 0.17 mms^{-1} during excavation of the concrete primary lining. The magnitudes were at least x1.7 lower than the corresponding predicted vibration.

Internal VDVs calculated over 16 hour daytime and 8 hour night-time periods from the vibration data were up to 0.05 $ms^{-1.75}$, and fell significantly below the daytime LOAEL of 0.2 $ms^{-1.75}$ and the night-time LOAEL of 0.1 $ms^{-1.75}$ presented in HS2 Information Paper E23.

9 UPDATED GBN&V PREDICTIONS

The results of the TBM and SCL surveys were used to refine the numerical modelling and update the predictions at receptors located along the remainder of the HS2 Chilterns tunnel route. This was undertaken to help inform Align JV's community liaison strategy in the communities that could still be affected by GBN&V generated by tunnelling activity along the remainder of the route.

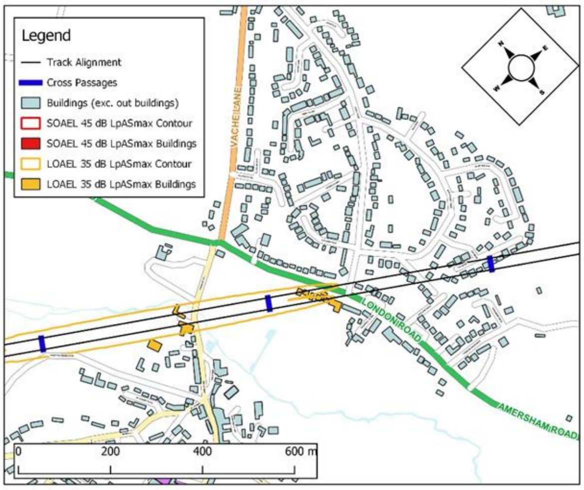

Figure 9 Groundborne noise contours through Chalfont St Giles after re-calibration of the vibration source term.

The updated predictions included a re-calibration of the vibration source terms applied in the numerical models using free-field measurements of groundborne vibration. For the reasons explained in Section 8, the RIVAS transfer functions were not adjusted in the model to ensure that any risks associated with the range of buildings along the trace yet to be encountered were allowed for in the contour calculations. After the source terms had been re-calibrated, groundborne noise predictions in buildings were reduced by up to 7 dB, and groundborne vibration magnitudes reduced by approximately 50%. The re-calibration exercise identified that the energy in the 200 Hz and 250 Hz 1/3-octave bands of the source term assumed in the detailed numerical modelling exercise were higher than those derived from the measurement campaigns. Re-calibration of the spectral shape of the overall energy in the source term resulted in lower magnitudes in the assessment results.

The retrospective predictions using the re-calibrated source term showed an overall reduction in the footprint of GBN&V effects as highlighted on Figure 9. For the areas above the tunnels yet to be constructed a total of 5 no residential properties along the entire Chilterns tunnel route were identified as likely to experience groundborne noise above the LOAEL criteria due to either TBM operation or CP construction activity. The refined model also showed that no remaining properties along the tunnelled route were predicted to exceed the SOAEL criteria. Groundborne vibration is anticipated to result in 1 no. LOAEL exceedance at a residential property along the Chilterns Tunnels route.

The refined modelling outputs were used by the community engagement teams to develop their strategy for the remainder of the tunnelled route yet to be constructed, in the knowledge that any SOAEL exceedances and hence provisions for temporary respite were unlikely. The refined modelling outputs also confirmed that there was low risk of any adverse effects on sensitive activities and vibration sensitive equipment usage at Amersham Hospital.

10 SUMMARY AND CURRENT STATUS

At the time of writing this paper Align JV has tunnelled approximately 80% of the of the 16km Chiltern Tunnels, and the Cross passages are over half way through the programme.

The Align JV has adopted a staged approach to the management of risks associated with groundborne noise and vibration from tunnel construction activities. Using an initial scoping approach enabled the potential risks to be raised and recorded early in the process. Those initial risks were then managed through the collaborative working between the construction, environment, noise, community engagement and engineering teams at Align JV, HS2 and with the local authorities. Subsequent stages in the study were designed to enable the continuous review and refinement of the assessments with increased certainty.

This approach also allowed for continual adaptation of the community engagement strategy, based on contemporary data and assessments. Providing information to the community on groundborne noise and vibration was identified by Align JV early on to be a critical measure for managing any widespread adverse response from communities, especially considering the absence of other practicable mitigation measures for tunnel construction works.

Where numerical modelling is deployed for detailed assessment purposes, it is important to ensure that models are verified with measurement data, to enable re-calibration and refinement. Due to the variability in the buildings within communities overlying the tunnels and to maintain a cautious approach to the risk assessments, assumed building response functions must correspond to worst case conditions.

Predictions of VDV appear to be at least an order of magnitude above measured VDVs due in part to the cautious approach applied to the vibration transfer functions and other assumptions applied for this study.

Individual and infrequent impulsive activity associated with some of the ring installation activities were found to contribute to some of the highest groundborne noise levels measured inside buildings during the surveys. Whilst sporadic occurrences of this nature were not considered to introduce adverse effects on the quality of life or wellbeing of building occupants, this effect was not anticipated during the risk assessments and is an area for further research into the control measures by reviewing the automated and manual construction processes involved in ring installation.

Exposure to groundborne noise and vibration typically lasted up to 3 days during a TBM pass.

The project has to date received only minimal complaints from the community during the tunnel construction works at the worst affected communities in the area reported in this study, the majority of which were related to CP construction. This is considered to be as a direct result of the comprehensive nature and timing of the community engagement activities deployed in advance of the TBMs approaching the most sensitive receptors.

The field surveys found that groundborne noise led to the only measured exceedances of the project's thresholds for effects (LOAEL), whereas there were no exceedances of those for vibration. The few complaints received to date during both the TBM and CP works are also attributed to groundborne noise only. Align JV has to date successfully completed its tunnelling works at the most sensitive properties without any measured SOAEL exceedances.

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