Tunnelling induced ground-borne noise modelling

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ABSTRACT

Ground borne noise caused by tunnelling machinery vibrations can result in significant community annoyance. A three dimensional ground model can be utilised in the modelling of tunnelling vibration and the resulting ground-borne noise. The progress of the tunnelling machinery can be input into the model such that the ground borne noise impact can be predicted for a given machine location, the affected properties can be identified and the duration of the excessive noise can be predicted. This paper presents the results from a noise model that predicts the location and duration of ground-borne noise impact from tunnel boring machines and roadheaders. The model outputs can be utilised to inform the project stakeholders and the community of potential noise issues and to schedule noise management programs.

INTRODUCTION

Ground borne noise from tunnelling is the noise generated by ground vibrations that are initiated by the cutting blades of tunnelling equipment impacting the ground materials. Ground-borne noise is sometimes referred to as structure-borne noise, re-radiated noise or re-generated noise. The latter terms are misleading because ground borne noise is the result of surface vibration caused by machine interaction with the ground and is not the result of a noise that is later re-radiated or re-generated.

Ground borne noise caused by tunnelling operations have the potential to cause significant community annoyance because, in general the operations are continuous twenty four hours per day. The noise is generally characterised as a low rumbling sound, however, the frequency can vary depending upon the machinery that initiates the vibration and the receiving environment.

A number of large tunnelling projects have been recently undertaken in the Brisbane area resulting in a need for modelling and monitoring of ground borne noise resulting from tunnelling operations. In particular, the prediction of potential ground borne noise impacts can allow for better planning of construction activities by;

- predicting the cost of relocating highly impacted residents
- informing the community consultation process
- scheduling activities to minimise noise impact or duration of impact
- installing mitigation measures, where practicable, prior to construction.

The paper discusses the modelling of ground borne noise from Roadheaders and Tunnel Boring Machines (TBM) although the principles could be applied to many construction noise and vibration planning

Roadheaders

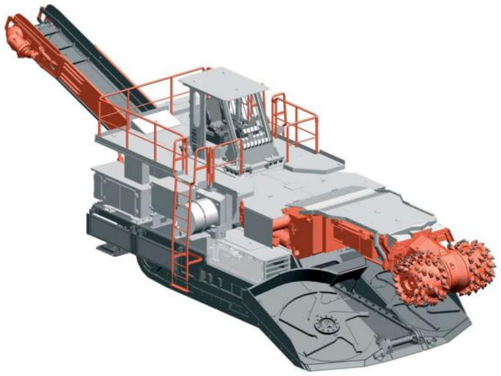
A roadheader consists of a rotating, cylindrical or spherically shaped head with cutters that claw at a soil or rock face. The machine is normally manoeuvred into position and the removed material is deposited onto a conveyor where it is transported to the rear of the machine. The material can be then be removed completely from the tunnel by additional conveyors or by a truck. Figure 1 shows the Sandvik MT720 Roadheader which is currently in use in Brisbane. Typically, for the projects investigated in Brisbane, the roadheaders will complete approximately 6m of tunnel per day although progress is clearly dependant upon the strength of the excavated material.

TBM

TBM typically consist a large rotating cutting wheel in front of large metal cylinder(s) known as shields as well as trailing control and ancillary mechanisms. Behind the cutting wheel is a chamber where the spoil is removed using conveyors to the rear of the machine.

The cutting wheel is moved forward by hydraulic jacks supported off the finished tunnel walls. When the cutting wheel has reached maximum extension the TBM head is braced against the tunnel walls and the rear section of the TBM is dragged forward.

Figure 2 shows the Herrenknecht Earth Pressure Balance (EPB) TBM similar to those employed on projects in Brisbane. Typically, for the projects in Brisbane, the TBM will travel approximately 20m per day. Once again the progress will depend upon the strength of the excavated material.



Source: Sandvik Construction and Mining

Figure 1. Sandvik's MT720 Roadheader

Source: Herrenknecht

Figure 2. Herrenknecht (EPB) TBM

ROADHEADER AND TBM VIBRATION

Dominant frequencies

For each cycle of motion, the ground vibration wave loses a small amount of energy that is required to overcome friction and other opposing forces. This loss of energy is called material damping since it is a function of the material deformation properties. The decay in vibration energy is a function of energy loss per cycle and not distance. Hence, the dominant frequency tends to reduce with distance because the lower frequency components have undergone fewer cycles and lost proportionally less energy.

The dominant frequency generated by a given tunnelling machine varies with the type of machine and also ground material. Thus, it is important to have undertaken testing or have an understanding of the machine and ground types for a given study area in order to be able to predict the ground vibration.

Figure 3 shows a typical vertical vibration spectra for a 12.4m diameter TBM operating in soft ground.

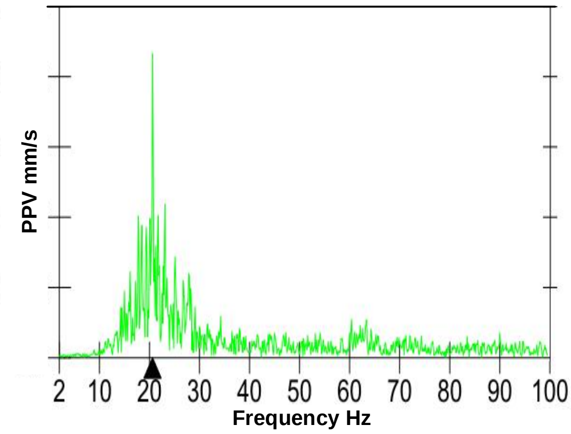


Figure 3. Typical TBM frequency spectra

The vibration from roadheaders has been found to be higher than that from TBM's and measured results indicate the dominant frequency centres in the 80-100Hz band.

Vibration propagation

The vibration propagation will depend largely upon the source frequency and the local ground properties. In this study the vibration propagation was based on measured vibration levels that were then fitted to a propagation equation of the following form. Equation 1 is specific to the machine and the local area.

$$PPV = \frac{K}{d} e^{-\alpha d} \qquad [1]$$

PPV	Peak particle velocity
d	Distance in metres from the source
K & α	Site / machine specific operators

The vibration analysis for this study was undertaken by a third party and hence specifics of the propagation equations cannot be included in this paper due to a confidentiality arrangement. The equations are based on the peak particle velocity (PPV) at the dominant vibration frequency for a given machine.

If the machine vibration is measured at a number of locations at varying distance from the source then the site specific operators can be determined as shown below.

$$\alpha = -\frac{\ln\left(V_2 d_2 / V_1 d_1\right)}{\left(d_2 - d_1\right)} \qquad [2]$$

$$K = \frac{V_1 d_1}{e^{-\alpha d_1}} \qquad [3]$$

V_1, V_2	Measured PPV at distance d_1 and d_2 respectively

Figure 4 shows a typical vibration propagation curve for TBM vibration at the dominant frequency. The site specific operators must be measured at a number of representative locations throughout the study area in order to account for varying ground types.

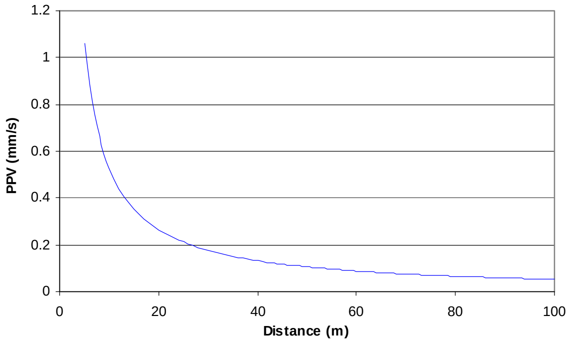


Figure 4. Typical TBM vibration propagation

GROUND BORNE NOISE PREDICTION

In general the ground borne noise generated by tunnelling activities will create annoyance long before the actual vibration can be perceived. Audible noise occurs within structures when vibration is transmitted into the building through foundations or other parts of the building in direct contact with the ground. The vibration causes the oscillation of floors, ceilings, walls and other objects in the receiving room which then radiate sound.

The root mean square (rms) vibration level in octave frequency bands allows the potential ground borne noise to be predicted using the empirical formula [4] (Kurzweil 1979) later validated for buildings above London Underground tunnels using data acquired by the Transport Research Laboratory (TRL) (Greer, 1993).

$$L_p = 20\log_{10} V_{rms} + 93 \qquad [4]$$

L_p Calculated 1/3 octave or octave band sound pressure level inside the receiving room (dB re 20µPa)

V_{rms} The rms vibration velocity in 1/3 octave or octave band (mm/s)

It was also noted (Greer, 1993) that the prediction was more reliable when applied to the free field vibration rather than the measured floor vibration and that noise levels can be reasonably predicted for terrace houses without considering the transfer functions between the free field and floor vibration levels.

It has been documented that this prediction method may be overly conservative for tunnelling in soft ground (Hiller, Bowers 1997, Hiller, Bowers, Crabb 2001), however, in the case of this study it was considered appropriate for an impact assessment procedure.

MODELLING PARAMETERS

The local terrain contours can be converted to a digital ground model (DGM) that can be used to create a 3D model of the area surrounding the tunnel. The building locations and the tunnel alignment can then be imported into the model. The alignment can be divided into sections of a predetermined length depending upon the resolution required for the assessment.

At each point on the alignment, the distance (slope distance, *d*) from the source to each receiver is calculated as shown in section in Figure 5.

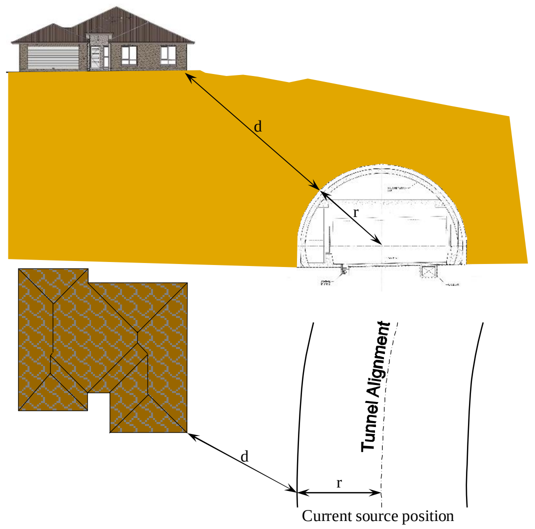


Figure 5. Calculation of slope distance

The vibration level and predicted sound pressure level can be calculated at each receiver for each given source location using equations [1] and [4] respectively.

The maximum sound pressure level can then be calculated at each receiver surrounding a given alignment and the extent of the noise impact from each alignment can be estimated.

The construction schedule can also be entered into the program so that each point on the alignment can be associated with a machine type, site operators and a time. In this way the impact at each receiver can be predicted at a given point in the construction schedule and the impact of multiple tunnelling machines operating consecutively can also be predicted.

RESULTS

Measured and predicted sound pressure levels

At this stage of the assessment, limited on site measurements have been conducted. Figure 6 shows a comparison of the predicted internal sound pressure levels with the measured sound pressure level for a given vibration level. The measured data was recorded by a third party and hence the magnitude of the sound pressure levels cannot be shown due to a confidentiality arrangement.

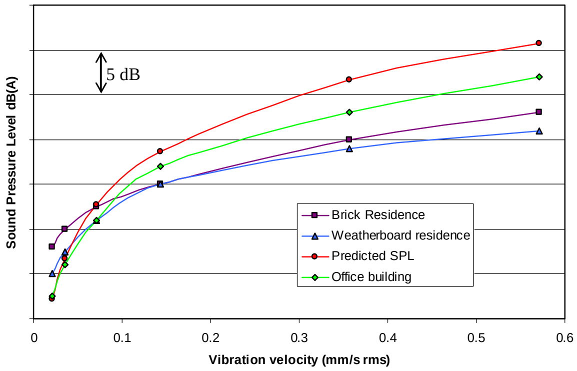


Figure 6. Comparison of measured and predicted sound pressure level

The frequency spectrum of the roadheader was not recorded for the measured vibration results. As a result, the predicted results have been calculated based on an assumed frequency of 80Hz based on data for other sites.

As with previous studies, it appears that the Kurzweil formula [4] is slightly conservative, however, the data is not currently comprehensive enough to suggest modifications. Given that planning and risk assessment are the primary goals of this model, a conservative approach has been considered acceptable and the calculation have been undertaken with formula in it original form.

Modelled sound pressure levels

The modelled data can be utilised in a number of ways.

- Recording the maximum level from each point on the alignment allows the extent of the noise impact to be predicted based on a single machine operating at a given time. These contours represent the maximum levels that will be measured over a period of time.
- Recording the noise impact from individual machines and summing the results allows the prediction of simultaneous machine operations at a given moment in time. These contours can be combined to give the maximum impact over a period when simultaneous operations will occur.

Figure 7 shows the maximum ground borne noise contours for a roadheader cutting a single tunnel. It should be noted that these contours are the prediction of sound pressure levels inside buildings that are located within a given contour band.

Figure 8 shows the noise contours for a period of time with four roadheaders operating consecutively. The terrain model used to generate Figures 7, 8 and 9 is not representative of the location shown because this information is currently confidential. The left hand side of the contours shows the effect of a steep incline on the predicted noise levels.

Figure 9 shows the noise contours for a moment in time with four roadheaders operating simultaneously.

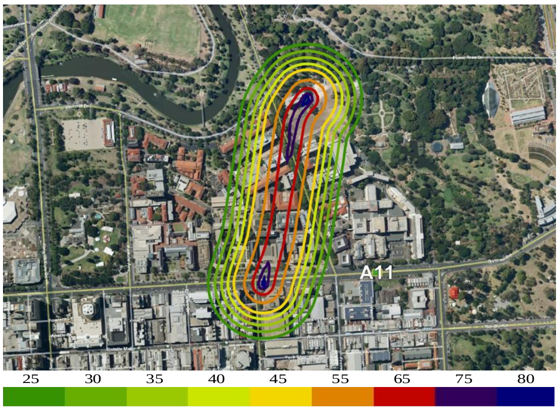


Figure 7. Maximum ground borne noise from a single roadheader

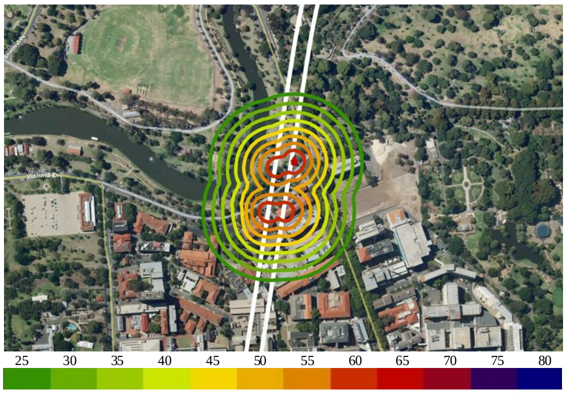


Figure 8. Maximum ground borne noise contours for consecutive operation of four road headers

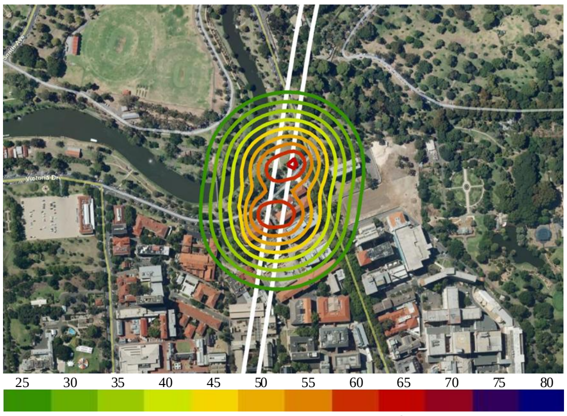


Figure 9. Ground borne noise contours for simultaneous operation of four road headers

If the work schedule is known, the location of a given machine can be associated with a time and the entire project can be mapped and animated. This allows the maximum impact to be viewed at any given time and mitigation and management measures can be planned along with the work schedule.

Figure 10 shows the internal noise impact at a residential receiver over a period of time. The operations during this period are as follows.

1. The TBM alignment passes the house at a minimum distance of 30m.
2. On the second day of the period, a roadheader begins cutting the first cut of a ramp starting approximately 50m from the house finishing approximately 90m from the house.
3. After the tenth day, the road header returns to the start of the ramp and begins the second stage cut of the ramp.

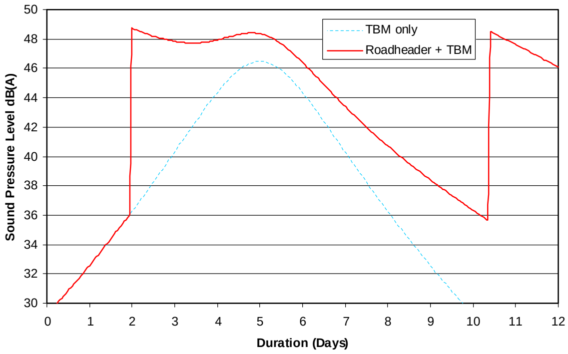


Figure 10. Predicted ground borne noise for a TBM and roadheader operation

CONCLUSIONS

The limited field work to date confirms the conclusion of earlier studies, that the internal noise prediction methodology (Kurzweil, 1979) gives slightly conservative results. At this stage modifications to the formula have not been suggested.

The vibration and internal sound pressure level algorithms can be incorporated in to a digital terrain model and integrated with project work schedules in order to provide a useful tool for the prediction of ground borne noise and vibration impact.

Using this prediction method, work schedules can be designed to minimise and manage ground borne noise impact by observing the entire project impacts prior to construction commencing.

The scheduled noise prediction could be expanded to include noise from other construction noise sources

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