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A Review of Prediction Methods for Ground-Borne Noise due to Construction Activities

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ABSTRACT

The generation of ground-borne noise inside receiver buildings due to nearby construction works can cause significant community impact and impose difficult constraints on construction activities. Several methods exist to predict ground vibration from permanent operational sources; however the suitability of some of these methods to predict ground-borne noise from construction activities are not well known and have not yet been thoroughly tested. This paper presents an overview of some of the various methods available to estimate ground-borne noise levels from construction activities and discusses the advantages and limitations of each.

INTRODUCTION

The generation of ground-borne noise inside receiver buildings due to nearby construction works can cause significant community impact and therefore needs to be assessed prior to construction commencing.

It would be advantageous to be able to reliably and efficiently predict the ground-borne noise impact resulting from proposed construction activities, including the effect of all relevant parameters and variables, since it would allow investigation of any opportunities that may exist to implement mitigation treatments.

However, the prediction of vibration propagation through soil is a complex task, made difficult by the inhomogeneity of the vibration propagation medium (ie. soil and/or rock). Several methods have evolved to predict ground vibration from various operational sources; however their suitability for prediction of ground-borne noise from construction activities is not well known and has not yet been thoroughly tested.

For instance, the generation and propagation of vibration and ground-borne noise has been extensively studied for the particular case of underground rail movements, and many well-established techniques now exist for this task. However the literature is comparatively sparsely populated in regard to discussion of the suitability of those same prediction methodologies for a slightly different purpose: namely the construction of underground structures.

Another important consideration is the relative simplicity, speed and accuracy of the various methods when used for predicting the impact from construction activities. Since construction activities are temporary and of relatively short duration, the aims of the modelling exercise will likely have different goals and priorities in comparison to an investigation for a permanent vibration source, and hence it may be appropriate and/or desirable to sacrifice modelling accuracy with ease of constructing, running and modifying models.

BASIC THEORY

The prediction of ground-borne noise levels from construction activities requires knowledge of the input vibration forces from the vibration source(s) into the cutting face, knowledge of the vibration transmissibility of the surrounding medium, and knowledge of the receiver building's vibro-acoustic response. The conversion of this vibration energy into sound pressure within the receiver building depends upon the coupling of the soil & the building's foundations, the structure's response including floor-to-floor attenuation and amplification due to resonance, the radiation efficiencies of the internal structural elements, and the room's acoustical properties.

Beginning with a known input vibration spectrum at the cutting face, it is possible to predict the resultant ground-borne noise levels within a receiver building using either semi-analytical and/or empirical techniques, or by numerical modelling.

The inherent variability and inhomogeneity of the soil and rock propagation medium means that site-specific geological information must be accounted for somehow in whatever prediction methodology is to be used.

Ground vibration propagates through the soil or rock as waves, so that the amplitude generally decreases with distance from the source. There are several different types of ground vibration waves, which propagate through different mechanisms and consequently exhibit different behaviours.

The types of waves that are usually the most important are:

- Compressional waves [primary ('P')-waves],
- Shear waves [secondary ('S')-waves], and
- Rayleigh waves ['R'-waves]

The wave speeds for the P, S & R waves are c_P, c_S and c_R respectively, given by:

$$c_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{1a}$$

$$c_S = \sqrt{\frac{\mu}{\rho}} \tag{1b}$$

$$c_R \approx c_S \frac{0.86 + 1.14\nu}{1+\nu} \tag{1c}$$

where ρ is the material density,

λ and μ are the Lamé constants, given by:

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \tag{2a}$$

$$\mu = \frac{E}{2(1+\nu)} \tag{2b}$$

in which E is Young's modulus, and ν is Poisson's ratio.

In eqs. (1a) and (1b), $\lambda + 2\mu$ is the bulk modulus and μ is the shear modulus G.

For soil or rock, compressional (dilatational) waves travel at wave speeds of 2.5-4 times the speed of shear or Rayleigh waves.

If the soil is saturated, another wave type may exist where the compressional waves in the fluid are coupled with the compressional waves in the soil, called Biot waves.

The rates of attenuation from ground vibration sources depend on the frequency spectrum of the input vibration forces and also the dominant types of waves generated by the vibration source. For example, vibration from equipment that generates higher frequency vibration such as a rock tunnel boring machine attenuates faster with distance than vibration from low-frequency sources. Separately, vibration from equipment that generates primarily body (compression) waves such as a tunnel boring machine attenuates faster with distance than vibration sources that generate principally surface waves such as a vibratory roller (Dowding 1996).

Attenuation of the different wave types due to geometrical spreading is given by (Dowding 1996):

$$\dot{u}_2 = \dot{u}_1 \left(\frac{R_1}{R_2}\right)^n \tag{3}$$

where

$\dot{u}_2, \dot{u}_1$ are peak particle vibration velocities at distances R_1, R_2 respectively, and

n = 1	for body waves (spherical compression waves)
n = 2	for surface body waves
n = ½	for Rayleigh waves

In close proximity to the source, compression waves dominate the ground vibration excitation. However, at large distances from construction sources, Rayleigh waves dominate the received vibration amplitudes due to a combination of geometrical spreading and frequency dependence of attenuation.

CURRENT METHODS & MODELS

Analytical solutions of boundary value problems can only be obtained for problems with very simple boundary conditions. For example, analytical solutions could be found for the simple case of the excavation of a circular tunnel in a homogeneous rock mass, however this is not a realistic scenario for practical tunnelling (Beer, Smith & Duenser, 2008).

The most well-known methods for prediction of ground vibration and ground-borne noise are as follows:

- Theoretical/(Semi-)Analytical
- In-situ testing/field measurements – Modular Prediction Approaches
- Empirical prediction/Direct Measurement Prediction Model (DMPM), and
- Numerical Methods

A discussion and comparison of the advantages and shortcomings of these alternative methods is available in the literature for railway induced ground vibrations (Hung & Yang 2001; Jones, Hussein & Hunt 2010; ISO 14837-1:2005(E)). However, no mention is given regarding the applicability of the various methods for prediction of construction impacts.

Semi-Analytical Approach

A general vibration propagation formula which includes the effect of internal damping losses in the soil is:

$$A(r) = A(r_0)e^{-\frac{\omega\eta}{2c}.r} \tag{4}$$

where A is the vibration amplitude, r is the source-receiver distance, ω is the frequency in rad·s^{-1}, η is the soil loss factor (which can be frequency-dependent) and c is the compressional or dilatational wavespeed.

Vibration from Railways

A useful semi-analytical approach for vibration from railways is given in (Ch 16) of *Transportation Noise Reference Book* (Remington, Kurzweil & Towers 1987), described as the 'Ungar and Bender approach'. This method predicts the attenuation of vibration through soil with a simplified formula by neglecting all wave types except compressional waves. "In effect they have reduced a complex problem in elastodynamics to a simple acoustics problem".

This method is given in a form which assumes the vibration source is an (infinite) line source, such as a moving train.

The method also does not allow for any modification to account for unusual or complex situations. It is essentially a flat-ground model which assumes only simplistic changes in soil type in the direction of propagation.

The mathematical simplifications mean that this method is not ideally suited for use in situations where the soil is saturated, because the method neglects Biot waves.

The simplified vibration propagation formula for the attenuation from a tunnel to a receiver at distance x is:

$$A_T = A_s + A_d + A_i \tag{5}$$

where

$$A_s = 10 \cdot \log\left(\frac{r_0 + x}{r_0}\right) \tag{5a}$$

$$A_d = 4.34\ \frac{\omega\eta x}{c} \tag{5b}$$

$$A_i = 20 \cdot \log\left[\frac{1}{2}\left(1 + \frac{\rho_c c_c}{\rho_a c_a}\right)\right] \tag{5c}$$

r_0 is the tunnel radius

A_i is the attenuation of ground-borne vibration waves as they cross the boundary between two different soil types. For this relationship, ρ and c are the densities and wavespeed respectively in the two soils a and c.

This method could be adapted for construction activities by suitable modification of eq. (5a).

Pipe-in-pipe

The Pipe-in-pipe method is a semi-analytical technique that simulates ground vibration from train movements in tunnels by modelling the tunnel's concrete shell as an inner pipe and the soil as an outer pipe, and the equilibrium of stresses and displacement continuity is accounted for by coupling the two pipes together (Gupta et al. 2007), (Jones, Hussein & Hunt 2010). Since the method is developed and intended for use only for line sources (underground railways) it is doubtful whether this method can be adapted to use for modelling construction vibrations.

In-situ testing/field measurements – Modular Prediction Approaches

A useful field-measurement-based prediction methodology for ground vibration and ground-borne noise from train movements is published by the US Federal Transit Administration (Hanson, Towers & Meister 2006)

The modular prediction approach has been used by the US Federal Transit Authority since the 1980's (Ho & Wong 2010). In the modular prediction approach, the method is a combination of discrete modules for the vibration source, the propagation path, and the receiver.

In the modular prediction approach, the propagation path and receiver response can be empirically determined by a Borehole Impact Test.

This in-situ testing method has the disadvantages that it is expensive, intrusive to the community, time-consuming and requires a large number of test sites to produce any usable data for large-scale projects.

Nevertheless, it is currently the only available method which provides a considerable amount of confidence in the calculations of vibration propagation through the soil in the area near to where the testing is carried out.

It is published in the US FTA document as a means for predicting ground-borne noise from trains, however it is adaptable to the prediction of ground-borne noise from various construction sources.

With suitable modification, it can be used for prediction of ground-borne noise from finite length line sources such as certain types of TBMs, or from point sources such as a TBM's cutting face, road headers, or other powered mechanical equipment.

The general formulation is as follows:

$$\mathrm{Ln} = (\mathrm{EFL\ or\ FDL}) + (\mathrm{PSR\ or\ LSR}) + \mathrm{BCF} + \mathrm{BVR} + \mathrm{CTN} + \mathrm{SAF} \qquad (6)$$

where:

Ln ~ predicted ground-borne noise level

EFL or FDL ~ Excitation Force Level (for PSM) or Force Density Level (for LSM),

PSR or LSR ~ Point Source Response (for PSM) or Line Source Response (for LSM), transfer mobility from source to receiver

BCF ~ Building Coupling Factor, coupling loss at ground-building interface

BVR ~ Building Vibration Response - reduction or amplification within a structure from the foundation to the occupied areas

CTN ~ Conversion to Noise level from floor vibration velocity level

SAF ~ Safety factor for prediction uncertainties (5 or 10 dB is commonly used)

The appropriate choice to use the point source or line source model depends on the TBM type. For line sources, the appropriate length is in the range of 10m to 30m subject to the geology and TBM type (Ho and Wong 2010).

Application in TBM Projects

> Appropriateness of PSM and LSM:
>
> Using an appropriate point source [PSM] or line source model [LSM] is essential for accurate determination of TBM excitation force. There are two major dynamic excitation sources inside the TBM – the cutter force and the supporting forces. The cutter force is the dynamic impulsive forces acting on the excavation face by the cutter discs, which is an area force modelled as a point force acting at the centre of the excavation face. The supporting force is acted by the hydraulic cylinders on a supporting structure, in order to provide the thrusting pressure to push the TBM forward. The supporting structure depends on the TBM types. For EPBM, Slurry TBM and Soft/Mixed Ground Single Shield TBM, the support is provided by the continuous concrete segments embedded behind the TBM as it advances. The supporting force is more similar to a line source along the tunnel wall especially when a TBM is excavating through soil. For Gripper TBM and Double Shield TBM in rocks, the support is provided by the gripper shoe mounted to the rock, the supporting force is a point source acting at the gripper shoe. For Gripper TBM and Double Shield TBM in rocks, both cutting force and supporting force are point forces thus PSM is more appropriate for GBN prediction. For EPBM, Slurry and Single Shield TBM, PSM is still better than LSM in most cases, except in soil strata with low characteristic frequencies that LSM may be adopted.
>
> Source: Ho and Wong (2010)

CTN - Conversion of vibration to ground-borne noise in receiver buildings

After the ground vibration level at the receiver location has been predicted by the preferred modelling method, the ground-borne noise level can then be estimated within the receiver buildings. This can be accomplished either with semi-analytical methods, by empirical formula or via a separate, but linked numerical modelling approach.

An empirical relationship based on simultaneous measurements of building floor vibration and ground-borne noise should ideally be obtained in locations nearby and with similar parameters to the subject site. For instance, a series of measurements in buildings near the Toronto Subway System resulted in this empirical formula (Remington, Kurzweil & Towers 1987):

$$L_p = L_a - 20 \cdot \log|f| + 37 \qquad (7)$$

Where L_p is the ground-borne noise level in dB, L_a is the floor vertical acceleration level in dB re 10^{-6}g, and f is the frequency in Hz.

An alternative method to estimate ground-borne noise levels inside receiver buildings is given by:

$$L_p = 20\log V + 93 \quad (8)$$

where V is the rms vibration velocity in mm·s^{-1} assuming steady sinusoidal vibration (Hiller, Bowers & Crabb).

Alternatively, this conversion can be estimated from typical approximate acoustic parameters including the internal surface area of the room, the radiation efficiency of structural elements, the room volume and reverberation time. Typical conversion factor values of 23 and 27 dB(A) have been used on projects for residential units and educational institutions respectively when vibration level is relative to 10^{-6} in/s (West Island Line Environmental Impact Assessment, Final EIA Report, Oct 2008).

Alternatively, the conversion from vibration levels to ground-borne noise levels can be undertaken considering spectrum data showing the characteristic frequency of the strata and the room acoustic response.

For a rough estimate of ground-borne noise in dB(A) due to ground vibration in dB re 10^{-6} in/s, the conversion is about -30 dB, although for soft soil at long distance it would be about -40dB and for very stiff rock it would be about -20dB (Ho & Wong 2010).

At receiver distances commonly encountered in ground-borne noise prediction studies, different frequency ranges are important for different types of vibration sources.

For Tunnel Boring Machines (TBMs) ground-borne noise impact would be important up to about 160 Hz for tunnels in soil, and up to about 500 Hz for tunnels situated in rock (West Island Line EIA, Oct 2008).

Empirical Prediction/DMPM

The empirical method is based on using a database of previous measurements taken in similar situations and simply extrapolating and/or interpolating against distance in order to make predictions. However, ground-borne noise from construction equipment is very sensitive to various parameters including propagation distance, geology at the cutting face, and along the transmission path, equipment type, etc. It is usually not possible to find previous measurement data with all sensitive parameters the same. Without distinguishing the effect of source and path variations, DMPM generally has a high prediction uncertainty of ± 15dB(A) (Ho & Wong 2010).

Perhaps the least reliable Empirical Prediction method is to utilise a curve-fitted relationship based on correlated measured overall vibration velocity levels and overall sound pressure levels in dB(A). Such a method, while perhaps somewhat transferable between two extremely similar projects in the same immediate area, would not be appropriate to estimate impact from any other type of construction equipment and/or in any other location.

Empirical prediction formulae for several different major types of ground-borne vibration sources have been developed and summarised in the literature (Hiller & Hope 1997). Specific values of the constant k are presented to use in the general equation for a conservative estimate of ground vibration from impact piling, vibratory piling, vibratory compaction, dynamic compaction and bored tunnelling for use in eq. (9):

$$v = k\frac{\sqrt{W_0}}{r} \quad (9)$$

where

v = vibration peak particle velocity

k = site-specific value (empirically determined constant)

W_o = Theoretical source energy per blow, or per cycle.

Hiller & Hope (1997) also give some other relationships for some construction sources, also based on the $\frac{\sqrt{W_0}}{r}$ term.

As a more specific example, Murray (2003) gives a fitted curve for ground-borne noise from roadheader activity in the region of Sydney, Australia, where the geology primarily consists of sandstone rock, as follows:

$$L_{Aeq}(\text{dB}) = -9.1303 \times \ln|x| + 65.543 \quad (10)$$

As discussed above, this relationship is only appropriate for use in the same area (Sydney) with the same type of construction machine (ie. a similar type of roadheader). It cannot reliably be used elsewhere and/or for a different vibration source.

NUMERICAL METHODS

There are several numerical methods which can be used for prediction of ground vibration and ground-borne noise:

- Finite Difference Time-Domain Method (FDTD or FDM)
- Finite Element Analysis (FEA)
- Boundary Element Method (BEM)
- Statistical Energy Analysis (SEA)
- Hybrid techniques

Finite Difference Time Domain

The FDM is essentially a numerical solution of the wave equation (ISO 14837-1:2005). It performs step-wise calculations of the states of each discrete element in the time domain, solving the PDEs in small finite time increments.

> An important consideration is the nature of the propagating medium, which is frequently porous and in some, but not all, cases water-saturated. While the FDTD method can readily take account of layering and anisotropy in soil and rock, accurate modelling of losses due to material damping is subject to uncertainty, not only because of the lack of test data on soil loss factors, but also because of the difficulty in reconciling loss factors which can be accounted for by geotechnical principles with observed rates of decay. The mechanisms involved in the propagation of vibration through porous media are, however, understood, and are capable of inclusion in a FDTD algorithm so as to predict the additional wave type that occurs, and in particular the losses associated with its rapid attenuation.
>
> Source: Thornely-Taylor (2005)

The Finite Difference method, while potentially extremely powerful, requires a high level of mathematical skill, making it non-preferred by many practitioners. However, some practitioners have used the Finite Difference method successfully and effectively for prediction of vibration propagation from railways for many years (Thornely-Taylor, 2005). However, the reasons why the Finite Difference method remains unpopular for the prediction of railway vibration, may also hinder its chances of ever becoming popular for predicting vibration and ground-borne noise from construction activities.

Finite Element Analysis / Method [FEA/FEM]

The Finite Element method has been studied and developed extensively for the purposes of predicting ground vibration and is in widespread common use for prediction of ground vibration from both construction and operational sources. Its near-universal adaptability and versatility make it a popular choice and the constantly improving useability of the accompanying graphical user interfaces continue to make it attractive for use in many types of situations. However, simply because a tool is commonly used and is very user-friendly does not mean it is always the best tool in every situation.

An interesting point on the popularity of FEM for prediction of ground vibration from line sources such as trains and roads is that they are often modelled in 2-dimensions, as can usually be done for (semi-)infinite line sources. However, ground vibration from construction cannot generally be modelled using 2D FEM because most construction equipment are point sources and the geology and geometry of the propagation paths are usually complex profiles in the different compass directions.

If the FE method is used, it is essential that the wave-propagating behaviour of the ground is correctly modelled. In particular, non-reflecting boundaries must be simulated to correctly represent the infinite wave propagation past the boundaries of the model (Thompson 2009).

Nevertheless, FEM is widely used for prediction of ground vibration and it will likely remain a popular choice in spite of its drawbacks and limitations.

Boundary Element Method

Like the Finite Element Method and the Finite Difference Method, the Boundary Element Method is essentially a method for solving partial differential equations (PDEs) and is limited to situations where the physical problem can be expressed as PDEs. The BEM requires the re-formulation of the PDE by discretising an integral equation on the boundary of the domain. However, only certain classes of PDEs can be re-formulated, hence the BEM is not ubiquitous, in contrast to the near-universal adaptability of the FEM and the FDM (Kirkup 2007).

The volume of work published in the literature on the use of the Boundary Element method for prediction of ground vibration is relatively small in comparison to the apparent popularity of the Finite Element Method. This may be for several reasons:

- Due to the fact that, compared to the FEM, a considerably smaller number of people are working in this field the development of the method is falling considerably behind.
- "There has been a general misconception that because a fundamental solution of the problem must exist for the BEM to work, the method can only be applied to linear problems with homogeneous material." However: "...non-linear problems can almost as easily be solved [with the BEM] as with the FEM, by the repeated solution of linear problems and special methods may be employed to solve problems with heterogeneous material properties." (Beer, Smith & Duenser (2008))

An important consideration in BE modelling is:

> Since functions must be found which exactly satisfy the governing differential equation (DE) the BEM requires a solution of the DE. This solution must be as simple as possible because ... this is crucial for efficiency. Unfortunately, the simplest solutions which we can find (fundamental solutions) are due to concentrated loads or sources and are singular, i.e., have infinite values at certain points.
>
> Source: Beer, Smith & Duenser (2008)

However, to overcome this, Gupta et al. (2007) found that many of the difficulties associated with the concentration of vibration input forces can be overcome by modelling the volume of soil/rock in the immediate vicinity of the vibration source using FEM, and modelling the remaining majority of the propagation path from source to receiver with a coupled BEM model.

Like the FEM, the BEM may also be used to find the system eigenfrequencies (Wu 2000), a tool which may be useful when investigating the resonant room modes of the spaces within a receiver building, which should be considered when investigating ground-borne noise because of its characteristic low frequencies.

The Boundary Element method could be readily used to predict both the vibration levels at the ground surface as well as the sound pressure levels within the receiver building internal space(s).

Recently, significant advances have been made in the computation efficiency of the Boundary Element Method, using a technique called the "Fast Multipole BEM"

Hybrid models

In some circumstances it may be advantageous and efficient to firstly compute solutions for the source vibration input into the ground using FEM or FDM, and then to use BEM to compute the propagation of the vibration from the source to the receiver.

The ground-borne noise level within the receiver building could then be subsequently calculated with either a (semi-) analytical, empirical, or numerical method.

Therefore it is possible to model the source, propagation path and receiver space with a hybrid of different numerical methods. This approach would be effectively a computational version of the Modular Prediction Approach.

Gaul & Fischer (2005) state that "For the simulation of structural vibrations, the FEM is the method of choice in engineering practice...Thus, BEM-FEM coupling schemes are favourable for the simulation of the acoustic-structure interaction".

For underground railways, an 'extruded' cross-section can be modelled as '2.5-dimensional', 'wavenumber' or similar method. These methods solve a 2D FE/BE coupled model a number of times for different wavenumbers in the axial direction, and a 3D solution is then established by a reverse Fourier transform over wavenumber (Thompson 2009). It is difficult to imagine how this method could be extended to account for point sources such as from construction activities.

COMPARISON OF METHODS

BEM vs. FEM

A treatise on the comparison of FEM and BEM for several different ground excavation situations is given in Beer, Smith & Duenser (2008), concluding that: for problems involving infinite domains as they occur, for example in geotechnical engineering, the BEM is superior to the FEM in terms of efficiency, accuracy, and user friendliness.

Pipe-in-Pipe vs. Coupled BEM/FEM

Gupta et al. (2007) compared the Pipe-in-pipe method against a coupled Boundary Element-Finite Element model, discussing the advantages and limitations of both models and found that “The coupled periodic FE–BE model has a greater potential as it can account for the complex periodic geometry of the tunnel and the layering in a soil medium.” Although the PiP method is likely not suitable for construction vibration, the relative robustness and versatility of the coupled FE-BE model against semi-analytical techniques generally is noteworthy.

SUMMARY

It is apparent that no single prediction method is universally applicable for prediction of ground vibration from construction activities. The selection of the most appropriate tool(s) to estimate ground-borne noise from construction sources will depend on the type of vibration source, the type of ground the vibration will propagate through, and the purpose for which the vibration & noise predictions are required (ie. the stage of the infrastructure planning & design process).

In some cases, it may be efficient and appropriate to utilise a combination of tools, depending on the accuracy required and the speed and volume of calculations necessary. For instance, at a certain stage of an infrastructure project’s planning and design stage, an accurate estimate of ground vibration may be desired, but a quick and conservative estimate of ground-borne noise might be acceptable. In that case, a suitable strategy might be to predict the ground vibration using a numerical method and to estimate the ground-borne noise using a semi-analytical technique.

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