Measurement and Prediction of Construction Vibration Affecting Sensitive Laboratories

Kym Burgemeister (1), Kai Fisher (1) and Kathy Franklin (2)

(1) Arup Acoustics, Melbourne, Australia
(2) Arup Advanced Technology and Research, Sydney, Australia

ABSTRACT

Heavy mechanised construction works, for example, excavation, piling and vibratory compaction cause groundborne vibration due to the interaction of the machines with the ground. This construction vibration can be perceptible to humans, often adversely impacts on sensitive receivers located very close to the construction site and in extreme cases may cause structural damage to nearby buildings. An assessment of construction vibration impacts is therefore usually restricted to sites directly adjacent to construction sites. However, laboratory buildings for nano-science, electronics lithography, high-magnification electron microscopy or imaging are significantly more sensitive to vibration than conventional commercial or residential buildings. A theoretical analysis indicates that it is possible that construction vibration from particular machinery could exceed the usual sensitive laboratory vibration velocity limits (eg VC-E, 3 μm/s) at distances up to 100–150 m from the construction site. This could necessitate the implementation of restrictive limitations on construction sites at relatively large distances from laboratory buildings to avoid adverse impacts on vibration sensitive equipment and processes. In this study, predictions of vibration from typical heavy construction works at long distance are made using both geometric spreading and frequency dependant attenuation models. The results of the predictions are compared to long-distance vibration velocity measurements undertaken on typical development sites due to the operation of bored piling and vibratory compaction equipment. The measurement results show good agreement with the empirical predictions, and show that vibration from heavy construction works can be expected to exceed VC-E at distances of 100–150 m from the construction site.

INTRODUCTION

Groundborne vibration from heavy construction works, particularly excavation and foundation works, has the potential to adversely affect nearby receivers. The potential impacts commonly include subjective disturbance to human (and sometimes animal) occupants - between vibration levels 1–5 mm/s, or concern regarding building or infrastructure damage (between 5–50 mm/s). Due to the relatively high vibration levels necessary to be perceptible in adjacent buildings, these types of impacts are generally only of concern in immediate proximity to the construction works.

Recent construction vibration guidance (*Construction Noise Strategy*, 2007) suggests ‘appropriate distances’ of between 2-25 m are adequate to control vibration to prevent building damage, although they may not be sufficient to ensure reasonable amenity for human perception. Although these ‘rules of thumb’ may be a reasonable means of managing complaints, they do not translate well to the management of vibration impact for sensitive equipment, since these usually have more onerous requirements.

For example, laboratory buildings for nano-science, electronics lithography, or high-magnification electron microscopy or imaging are significantly more sensitive to vibration than conventional commercial or residential buildings. These types of buildings are commonly designed to achieve internal vibration levels between VC-E (3 μm/s) and VC-B (25 μm/s) (Ungar et al., 1990).

While this type of sensitive technical equipment is sometimes supported on local equipment-based isolation system or on vibration isolating floated floor systems, these systems usually increase the mobility of the equipment support, and almost always amplify low-frequency occupational vibration. It is therefore common to locate this type of equipment on at-grade or basement slabs to provide a solid, high-impedance and low-vibration base.

Furthermore, while exceeding specified vibration criteria may sometimes result in manageable temporary interruptions, for some laboratory research, even short-term vibration can result in the loss of many months or even years of research time.

This means that existing vibration sensitive facilities at laboratories or hospitals are highly sensitive to vibration from construction works, even when that construction is a considerable distance from the laboratory site. In turn, this means that vibration from construction works will need to be carefully managed during the construction process to minimise the potential for adverse impacts on the operation of the laboratories.

The extent of potential construction vibration impacts at large distances is subject to considerable uncertainty due to ground conditions, and there are few studies that particularly consider construction vibration on highly sensitive buildings (Amick & Gendreau, 2000). Arup has recently undertaken studies for several existing and proposed technical buildings for highly vibration sensitive equipment which will be subject to future construction works within several hundred metres of the equipment.

This paper documents the results from these construction vibration investigations for high-technology buildings. Initially, a desktop investigation was undertaken using empirical prediction equations, and combining measurement results from previous site investigations with geometric and frequency dependant propagation loss models. Site vibration measurements were also undertaken using high-sensitivity equipment at large distances for several ‘worst case’ construction processes - installation of bored piles (augering, vibrating casings), using a vibratory roller for ground compaction and general movement of heavy site equipment.

EMPIRICAL STUDY

Initially, an empirical study was undertaken using established empirical data for vibration levels generated by typical construction processes and equipment from published literature and previous site measurements.

The aims of the empirical study were to:

1. Identify construction activities that could potentially cause unacceptable vibration levels at the sensitive receiver.

2. Define vibration impact zones around the receiver and determine construction activities within these zones that could influence the vibration performance within the sensitive receiver.

In order to achieve these goals, predictions of anticipated vibration levels at various distances due to typical construction activities were required. This included prediction of vibration propagation over large distances for vibration sensitive facilities.

Vibration Propagation Models

Vibration in soil can propagate with various types of waves, propagating both on the surface of the soil and through the body of the soil. These different wave types travel at different speeds. Close to the source, it is expected that all forms of vibration will be important, but at larger distances, typically in the hundreds of meters, the relative levels of these vibrations can vary depending on the soil type. This is because different types of waves are attenuated at different rates due to their differences in speed and propagation methods.

There are two broad mechanisms that attenuate vibration as it propagates through the soil (Bornitz, 1931). These are

- **Geometric loss** – where attenuation is modelled by geometric spreading to match empirical data
- **Material loss** – where attenuation is modelled by frictional loss in the soil to match empirical data

Geometric loss is due to the spreading of waves as they propagate out from the source. The rate of loss depends on the type of wave.

Material loss is due to viscous behaviour of the soil and is a loss per unit distance travelled. It can also be considered to be frequency dependant, the attenuation increasing with increasing frequency (Woods & Jedele, 1985; Amick, 1999).

Typically, empirical work in the past has used either a geometric loss model, where the loss due to spreading is determined from regression analysis of measured data, or by using material loss with an assumed constant geometric loss.

Frequency Dependant Material Loss Propagation Model

Amick (1999) proposed a propagation model with a frequency dependant material damping loss function as shown in Equation (1). It defines the vibration level at location *b* relative to the vibration level at location *a*, and provides a damping constant for material loss. Assuming Raleigh wave propagation is dominant, γ is set to 0.5.

$$v_b = v_a \left(\frac{r_a}{r_b} \right)^{\gamma} e^{\rho \pi f (r_a - r_b)} \qquad (1)$$

Where;
v_a is the vibration level at location *a*
v_b is the vibration level at location *b*
r_a is the distance from the source at location *a*
r_b is the distance from the source at location *b*
γ is the geometric propagation loss term.
ρ is the material damping loss
f is the frequency of the vibration

Ranges of material damping loss, ρ, for various categories of soil types are shown in **Table 1** (Woods & Jedele, 1985).

Table 1 Soil Classes and Material Attenuation

Class	Description	ρ, $m^{-1}Hz^{-1}$
IV	*Hard, competent rock* (difficult to break with rock hammer): bedrock, freshly exposed hard rock	< 1.8x10^{-6}
III	*Hard soils* (cannot dig with shovel, must use pick to break up): dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock	1.8x10^{-6} to 1.8x10^{-5}
II	*Competent soils* (can dig with shovel); most sands, sandy clays, silty clays, gravel, silts, weathered rock.	1.8x10^{-5} to 6.1x10^{-5}
I	*Weak or soft soils* (Soil penetrates easily); lossy soils, dry or partially saturated peat and muck, mud, loose beach sand and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, topsoil	6.1x10^{-5} to 1.8x10^{-4}

Geometric Loss Models

Geometric loss models ignore the material damping (loss) coefficient (ρ in Equation (1)), assuming it is zero. To allow for different propagation losses, γ is varied. γ is generally selected based on soil type and typically varies between 0.5 and 2.0. In the initial empirical studies γ was set to 1.5.

It is expected that different site conditions will require different γ values, in addition, different types of vibration sources may in general have different γ values even for the same site. However due to large variation in measured vibration levels, determining a γ which varies by both vibration source and soil type is difficult. Usually in the case of prediction, unknowns about the soil type and input vibration levels in the soil are far more significant than variation in gamma between vibration equipment for short to medium range distances (up to approximately 80–100 m).

Empirical Vibration Source Levels

The UK Transport Research Laboratory (TRL) (Hiller & Crabb, 2000) has undertaken specific ground vibration measurements for a wide range of typical construction equipment and processes, across a wide range of distances and ground conditions. The TRL empirical data is widely used as the basis of construction vibration prediction, but is only validated for short to intermediate distances (up to 100 m)

The TRL data has been supplemented with vibration measurements recently undertaken by Arup for some excavation, piling and construction works on Australian sites.

For the purposes of the study empirical equations for the vibration levels of impact piling, vibratory piling, vibratory compaction, and mobile plant operation were used as follows (Hiller & Crabb, 2000);

Vibratory Compaction:

$$v_{res} = k_s \sqrt{n_d} \left[\frac{A}{x + L_d} \right]^{1.5} \qquad (2)$$

Where k_s= 175, n_d = 1, A = 1 mm, L_d = 2.5 m.

Percussive Piling:

$$v_{res} \leq k_p \left[\frac{\sqrt{W}}{r^{1.3}} \right] \qquad (3)$$

Where k_p = 1.5, W = 60 kJ and $r^2 = L^2 + x^2$, L = 27 m

Vibratory Piling:

$$v_{res} = \frac{k_v}{x^{\delta}} \qquad (4)$$

Where k_v = 160, δ= 1.3

In addition, Hiller (2003) determined linear function lines in the logarithm of velocity and distance for large quantities of pile data in the UK. The regression functions were used to predict the vibration level as a function of distance.

EMPIRICAL VIBRATION PREDICTIONS

Vibration predictions were conducted for a range of construction activities which have been categorised into:

- Piling
  - Screw/Augered Piling
  - Continuous Flight Auger Piling (CFA)
  - Impact Piling
  - Sheet Piling
- Vibratory Compaction
- General Mobile Plant Movement and Operation

Overall empirical vibration levels were determined using TRL (Hiller & Crabb, 2000) and Hiller (2003) equations as functions of distance from the source.

The predicted vibration levels at 20 m using TRL and Hiller were also used as reference levels for use in the geometric loss propagation models (ie Equation (1) with $\rho = 0$ and γ = 1.5).

Where spectra were available (from previous site measurements) at short distances, vibration levels as a function of distance have been predicted using the Amick (1999) frequency dependant propagation model in one-third octave bands. The soil type at the subject site was determined to be Class II. An initial value for the material damping $\rho = 6.1\times10^{-5}$ m^{-1}Hz^{-1} was used (see **Table 1**).

The spectra used for predicting vibration levels with the Amick (1999) model are presented in **Figure 1**.

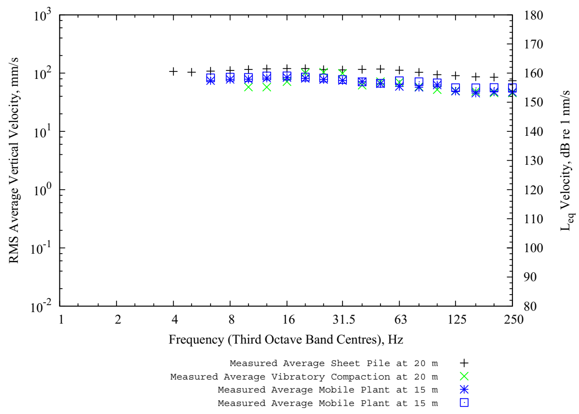

Figure 1 Source vibration velocity spectra measured at Australian sites for various construction activities.

Predictions of both overall vibration levels as a function of distance and frequency spectra are presented at the end of the following section.

Note that vibration using Equation (1) for augered piling was not possible due to lack of reference spectral levels.

CONSTRUCTION VIBRATION SITE MEASUREMENTS

Following the initial theoretical study using empirical data, site measurements were undertaken of actual construction vibration at the future site of a high-technology laboratory facility. The objectives of the site measurements were:

- To provide some actual measured vibration levels of likely construction activities at this site.
- Confirm vibration propagation predictions through the ground at the laboratory site for activity at surface and rock levels
- Particular investigation of vibration levels generated at standoff distances >100 m and for low levels of vibration around VC-E where there is little empirical data

Measurements of vibration levels generated at the laboratory site by various construction sources were made in December 2010. Vibration levels were measured using a Data Physics Quattro 4 channel data acquisition system and Larson-Davis 2 channel data acquisition system with PCB39312 and Brüel & Kjær 4370 high sensitivity accelerometers.

The accelerometers were installed in three different layouts for the various measurements. Accelerometers were mounted as follows to ensure good coupling:

Soil surface – Accelerometers were mounted using beeswax or mounting studs to the top of a wooden stake driven firmly into the ground at each measurement location.

Test pile – Accelerometers were mounted using beeswax to the concrete surface of a test pile installed at the site.

Measurement Borehole: - Accelerometer was fixed to the base of a heavy waterproof canister and lowered to the bottom of a site borehole.

The sensitivity (noise floor) of the combined accelerometers and data acquisition systems was confirmed to be below VC-E in each case.

Construction Activities

Site vibration measurements were undertaken at various distances from the following construction works:

- bored piling
- vibratory pile casing
- vibro-compaction using a vibratory roller
- general movement of mobile plant (eg piling rig, excavators)

Bored piling was selected for the measurements instead of impact piling because it is a common construction process, and it would be difficult to find a lower vibration alternative. It will also cause vibration at both rock level as well as in the softer soils above.

Vibro-compaction was selected because the input is fairly clearly defined in terms of magnitude and frequency. Moving the plant provides an indication of the effect of general plant and vehicle movements.

COMPARISON OF EMPIRICAL PREDICTIONS TO MEASUREMENT

Empirical predictions of vibration levels for the various construction equipment and processes are compared to the values measured at a future high-sensitivity laboratory site in **Figure 2** to **Figure 7**.

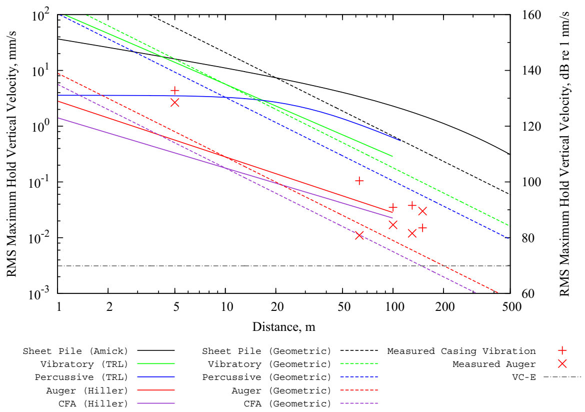

Figure 2 Comparison between empirical predictions and measurements of piling vibration velocity.

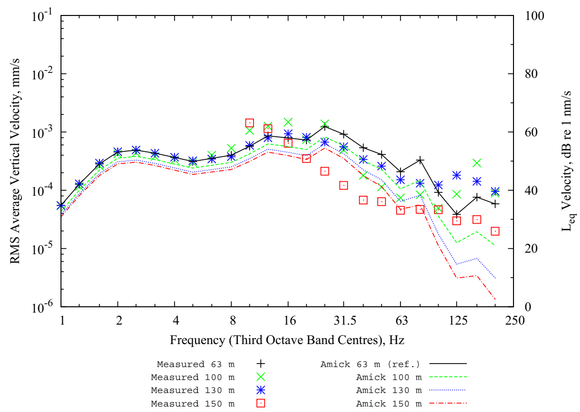

Figure 3 Simultaneously measured vibration spectra due to augered piling at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) relative to the vibration levels as measured at 63 m.

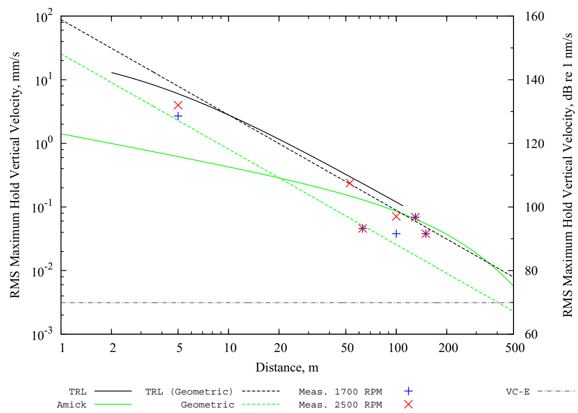

Figure 4 Empirical predictions of vibration due to vibratory compaction at different RPM. Measurements at future high sensitivity laboratory site are shown and compared to the VC-E vibration criteria.

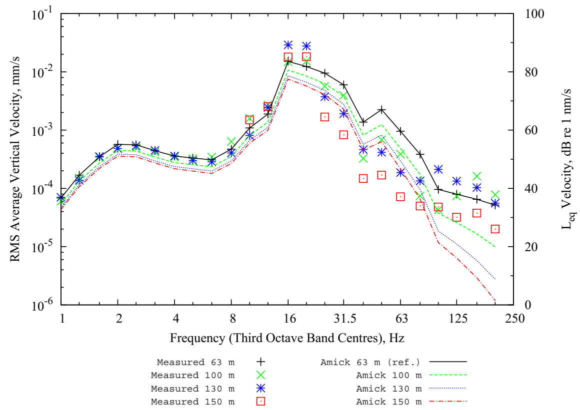

Figure 5 Simultaneously measured vibration spectra due to vibratory compaction at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) relative to the vibration levels as measured at 63 m.

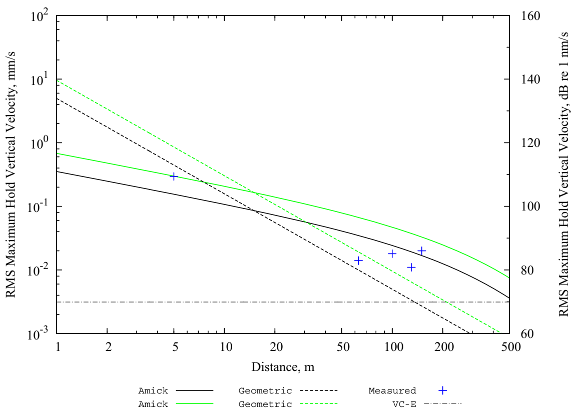

Figure 6 Empirical predictions of vibration due to various types of mobile plant operating. Measurements at future high sensitivity laboratory site are shown and compared to the VC-E vibration criteria.

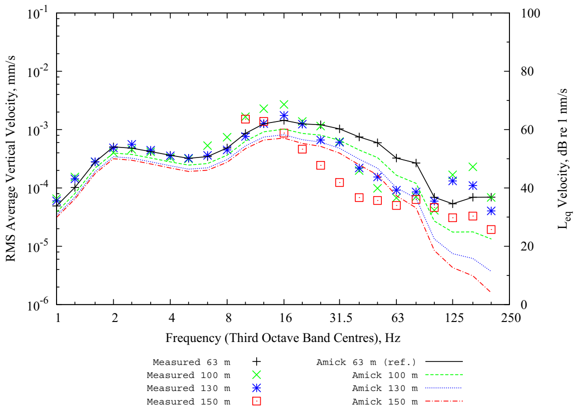

Figure 7 Simultaneously measured vibration spectra various types of mobile plant operating at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) relative to the vibration levels as measured at 63 m.

Discussion

The measured vibration levels generally show broad agreement with the empirical predictions, and confirm that construction vibration levels are likely to exceed the criteria for the most sensitive laboratory uses, even at distances of between 100–200 m from the construction works.

Clearly, this will place enormous constraints and management requirements on future construction works that are undertaken in the proximity of the laboratory sites.

Examination of **Figure 3**, **Figure 5** and **Figure 7** demonstrates the material damping loss as a function of frequency which was assumed ($\rho = 6.1\text{x}10^{-5}$) may not be large enough due to the slight over prediction in the frequency range approximately between 16 and 80 Hz. The high frequency (above approximately 100 Hz) is controlled the noise floor of the instrumentation. The slight over prediction also broadly corresponds to the slight over prediction for overall vibration levels which is observed in **Figure 4** and **Figure 6** at large distances.

Theoretical Predictions Using Class I Soil Type Propagation Loss

To test the applicability of the frequency dependant propagation model, a material loss constant of $\rho = 1.8\text{x}10^{-4}$ was tested. This corresponds to the upper limit for Class I soils (Woods & Jedele, 1985). The measurements have been compared to calculations using a Class I soil type and are presented in **Figure 8** to **Figure 13**.

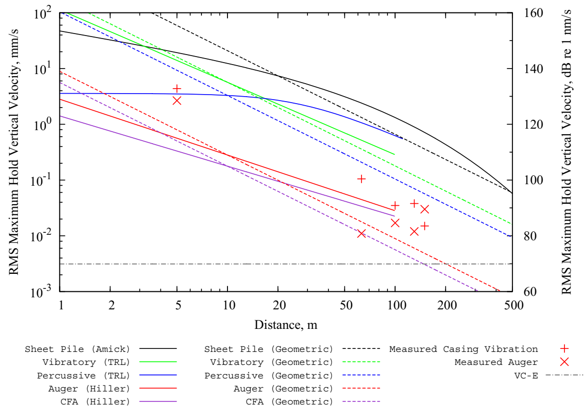

Figure 8 Empirical predictions of vibration due to various types of piling (frequency dependant propagation, $\rho = 1.8\text{x}10^{-4}$). Measurements at future high sensitivity laboratory site are shown and compared to the VC-E vibration criteria.

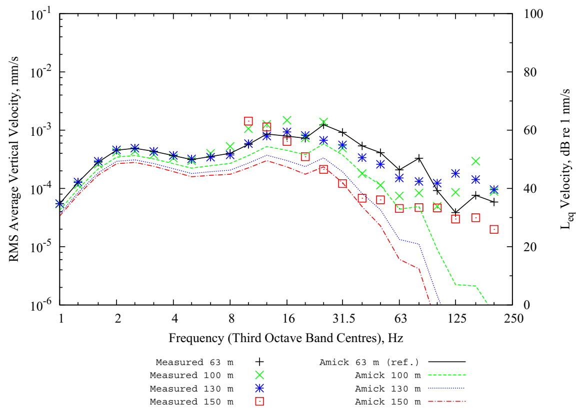

Figure 9 Simultaneously measured vibration spectra due to augered piling at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) ($\rho = 1.8\text{x}10^{-4}$) relative to the vibration levels as measured at 63 m.

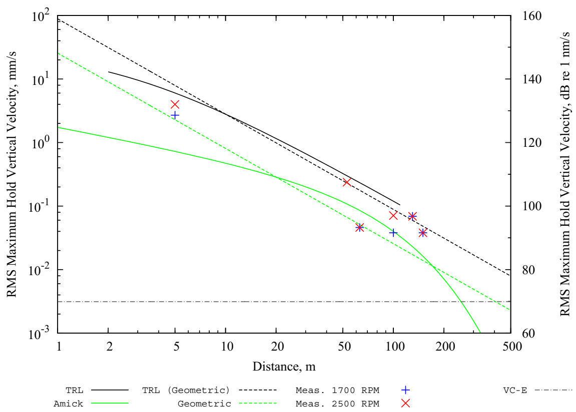

Figure 10 Empirical predictions of vibration due to vibratory compaction (frequency dependant propagation, $\rho = 1.8\text{x}10^{-4}$). Measurements at future high sensitivity laboratory site are shown and compared to the VC-E vibration criteria.

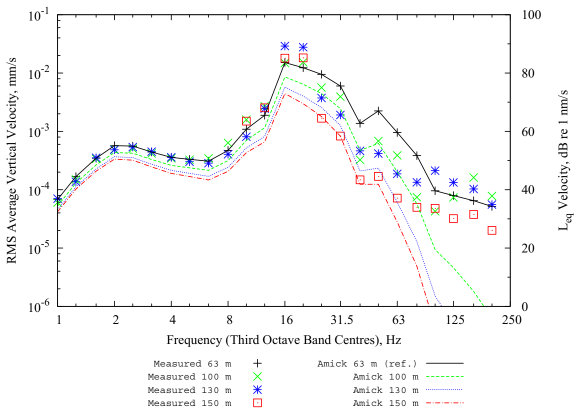

Figure 11 Simultaneously measured vibration spectra due to vibratory compaction at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) ($\rho = 1.8\text{x}10^{-4}$) relative to the vibration levels as measured at 63 m.

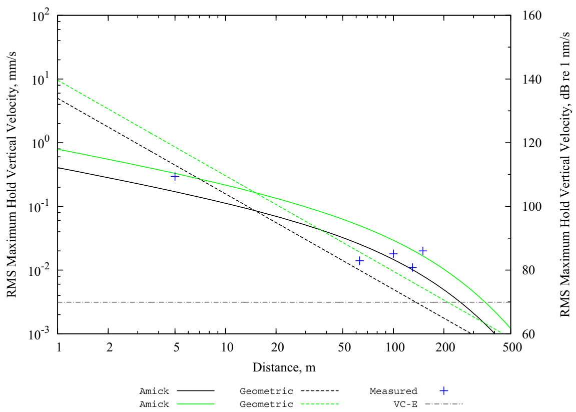

Figure 12 Empirical predictions of vibration due to mobile plant operation (frequency dependant propagation, $\rho = 1.8\text{x}10^{-4}$). Measurements at future high sensitivity laboratory site are shown and compared to the VC-E vibration criteria.

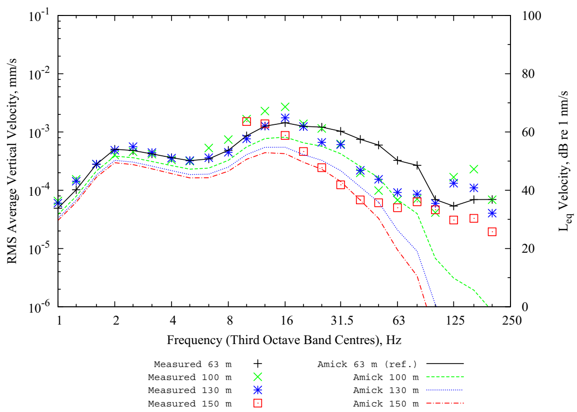

Figure 13 Simultaneously measured vibration spectra due to mobile plant operation at various distances from the source at future high sensitivity laboratory site. Theoretical prediction of the loss as a function of distance is presented using Equation (1) ($\rho = 1.8\text{x}10^{-4}$) relative to the vibration levels as measured at 63 m.

Discussion

The use of Class I soil instead of Class II appears generally to provide a marginal improvement to the agreement between the theory and measurement in the frequency range between approximately 10–100 Hz over distances between 63–150 m. However, variation in the measurement levels on site indicate that for the assumed model a propagation loss anywhere in the range of Class I soils is probably reasonable, particularly since the initial estimate used the upper limit of Class II (which is also the lower limit of Class I soils) also provided reasonable (although slightly high) predictions compared to measurement.

In general the frequency dependant loss agrees reasonably with measurement.

It is also noted that generally speaking the overall level predictions from both TRL (Hiller & Crabb, 2000) and Hiller (2003) were quite reasonable for the types of soil and activities examined in this study.

CONCLUSION

Generally speaking, for large offset distances (greater than 100 m from the source), a geometric loss alone is expected to be less accurate than a frequency dependant vibration propagation model. At large distances the behaviour of the overall vibration levels become non-linear, and in particular depends strongly on the source spectrum. For moderate distances (approximately 10–100 m) using a geometric loss for the overall vibration level appears to generally be a reasonable assumption.

Vibration activities with very strong low frequency components are more likely to agree with a simple geometric loss and those with more high frequency content are likely to either require a different value of γ for the same soil type or a frequency dependant propagation loss should be considered.

Due to the frequency dependant nature of the propagation losses, the input vibration levels are important for accurate predictions at large distances. This in turn means that input vibration levels for any given construction activity themselves will be dependant on the soil type.

To improve predictions, both frequency dependant propagation losses and also typical spectra at a defined reference distance could be documented for various construction activities and soil classes. This would enable selection of soil class and construction activity to determine the reference spectrum and then use of the propagation model to predict the vibration levels at large distances. A reference distance of 20 m is proposed as it is close enough that frequency dependant propagation is unlikely to have significantly dominated the overall level, and far enough that the assumed Raleigh wave propagation is likely to be dominant. Whilst this would not remove the need for vibration measurements for specific sensitive sites it may assist with initial site selection and desktop studies to evaluate risks associated with construction activities negatively impacting sensitive laboratories.

In general, the vibration velocity due typical construction works such as vibratory compaction and other activities which are usually considered to have relatively low impact, such as augured piling and general site equipment movements is expected to be considerably higher than the stringent VC-E vibration criteria, even at stand-off distances of between 100–200 m. This means that construction near to sensitive laboratories is likely to impact sensitive equipment and processes within the laboratories and will require careful management and in general will require on site measurement specific to the particular site due to the large variation in vibration levels due to specific site conditions.

REFERENCES

Amick, H 1999, ‘A Frequency-Dependent Soil Propagation Model’, *Proceedings of SPIE Conference on Current Developments in Vibration Control for Optomechanical Systems*, Denver.

Amick, H, Gendreau, M 2000, ‘Construction vibrations and their impacts on Vibration-Sensitive facilities’, *Proc. ASCE Construction Congress*, Florida.

Amick, H, Gendreau, M, Busch, T & Gordon, C 2005, ‘Evolving criteria for Research Facilities: I-Vibration’, *Proc SPIE Buildings for Nanoscale Research and Beyond*, San Diego, CA.

Bornitz, G 1931, *Uber die Ausbreitung der von Grozklolbenmaschinen erzeugten Bodenschwingungen in die Tiefe*, J. Springer

Construction Noise Strategy (Rail Projects), 2007, NSW Transport Infrastructure Development Corporation.

Hiller, D & Crabb, 2000, *Groundborne Vibration Caused by Mechanised Construction Works*, Transportation Research Laboratory

Hiller, DM 2003, ‘A comparison of noise and vibration from percussive and bored piling’, *Proc Underground Construction 2003,* 213-224.

Nelson, P ed 1987, *Transportation Noise Reference Book*, Chapter 16, Butterworth & Co.

Ungar, EE, Sturz, DH, Amick, H 1990, ‘Vibration control design of high-technology facilities’, *J. Sound and Vibration*.

Woods, RD, & Jedele, LP 1985, ‘Energy – Attenuation Relationships from Construction Vibrations’, *Vibration Problems in Geotechnical Engineering,* Proc. ASCE Convention, Detroit, October 1985.