University of Salford
A Greater Manchester University

HUMAN RESPONSE TO VIBRATION IN RESIDENTIAL ENVIRONMENTS (NANR209)

TECHNICAL REPORT 3

CALCULATION OF VIBRATION EXPOSURE

31 MARCH 2011

Gennaro Sica, James Woodcock, Eulalia Peris, Zbigniew Koziel, Andy Moorhouse, David Waddington

FOREWORD

This research was commissioned by the previous government.

The work was funded by the Department for Environment Food and Rural Affairs.

The views and analysis expressed in this report are those of the authors and do not necessarily reflect those of the Department for Environment Food and Rural Affairs.

PREFACE

This document is one component of the Defra project NANR209 'Human response to vibration in residential environments' final report.

The NANR209 Final Report consists of the following documents:

- Executive summary
- Final project report
- Technical report 1: Measurement of vibration exposure
- Technical report 2: Measurement of response
- Technical report 3: Calculation of vibration exposure
- Technical report 4: Measurement and calculation of noise exposure
- Technical report 5: Analysis of the social survey findings
- Technical report 6: Determination of exposure-response relationships

The project was performed at the University of Salford between January 2008 and March 2011. During that time the following University of Salford researchers worked on the project. David Waddington, Andy Moorhouse, Mags Adams, Geoff Kerry, Rodolfo Venegas, Andy Elliott, Victoria Henshaw, Eulalia Peris, Phil Brown, Andy Steele, Jenna Condie, Gennaro Sica, James Woodcock, Deborah Atkin, Nathan Whittle, Zbigniew Koziel, George Perkins, Natalia Szczepanczyk, Sharron Henning, Ryan Woolrych, Heather Dawes, Amy Martin, Maria Beatrice Aquino-Petkos, Laura Jane Buckley, Catherine McGee, Andrew Caunce, Valentin Le Bescond, Stephanie Jones, Dawn Smail, Andrew King, Lauren Hunt, Michael Gerard Smith, Tomos Evans.

The work by the University of Salford benefited from guidance by the Defra project steering group. The Defra project steering group consisted of Richard Perkins and Colin Grimwood on behalf of Defra, Colin Stanworth representing the interests of the British Standards Institution working group for BS6472, Rupert Thornely-Taylor representing the interests of the Association of Noise Consultants, and Henk Miedema, Sabine Janssen and Henk Vos from TNO (Netherlands Organization for Applied Scientific Research).

This project benefited from guidance in the design of the vibration measurement equipment from the suppliers Guralp Ltd.

The peer review of the railway questionnaire was performed by Jim Fields, Larry Finegold, Evy Öhrström, Peter Brooker, and Gary J Raw.

This research would not have been possible without the kind cooperation of the residents that took part in the field trials.

The work presented is research performed by the University of Salford funded by Defra.

CONTENTS

LIST OF FIGURES

1 EXECUTIVE SUMMARY

The Technical Report 3 describes the research undertaken to develop a methodology by which human exposure to vibration in residential environments can be calculated. That work has carried out by the University of Salford supported by the Department of environment food and rural affairs (Defra). The overall aim of the project is to derive exposure-response relationships for human vibration in residential environments. This document in particular focuses on the methods used to calculate vibration exposure from measured vibration signals due to different sources.

The main objective of this report is to describe the different approaches used for calculating the different source-specific exposure. Reported here are findings obtained and a description of the feasibility of the methods used for evaluating exposure for different sources. In addition, an evaluation of the uncertainty related to the exposure calculation is considered.

2 INTRODUCTION

This report describes the methodologies used for the quantification of the human exposure to vibration in the residential environments covered by the social survey reported in Part 2. Each of the source types is considered separately, railway, construction and internal activity. Evaluation of the associated uncertainties is also considered.

2.1 INTRODUCTION AND FORMULATION OF THE PROBLEM

The exposure is defined as the 'quantity' of vibration to which a hypothetical resident is exposed inside their property from vibration sources that are outside their control, assuming that they remain indoors during the period of exposure. Vibration affecting residential environments can be classified in the following way:

- Transitory or impact.
- Continuous or steady-state.
- Random or pseudo-steady-state.

In order to evaluate human exposure, the vibration needs to be considered in the frequency range encompassing the range of human sensitivity. The magnitude and duration of the vibration need to be taken into account and possibly also other temporal aspects such as its repeatability.

The vibration considered in this study consists of ground and structural vibrations caused by manmade process, specifically:

- Railway activity.
- Construction activity.
- Human domestic activity

In order to achieve the high number of case studies required for development of exposure-response relationships, the residential areas considered were those with a high density of dwellings situated less than 100 meters from the above vibration sources. In these situations it can be helpful to break down the generation, transmission and perception of vibration into the following elements:

- Source – defined as the region where the vibration is created.
- Path – defined as the region through which the vibration is transmitted.
- Receiver – defined as the part of the building where the vibration is felt, typically a floor.
- Human body – which is most sensitive to vibration in the frequency range from 0 to 80 Hertz (Griffin 1996).

In the case of railway and construction activity, the source is external to the property. In the case of the human activity the vibration is initially generated inside the building where it is felt.

In the case of both internally and externally generated vibration, each region, source, path and receiver, is involved in the process of vibration transmission and may either magnify or reduce the level of vibration during its passage. Therefore, these factors need to be taken into account for a complete understanding and estimation of the exposure. The 'point of entry' is defined as the contact surface between the human body and the vibrating receiver (floor). Here, the vibration is felt more if its frequency is close to maximum sensitivity of the human body which is generally around 10 Hz for a standing position. Furthermore, the perception of vibration may change with posture and with the activity itself; for example the vibration is likely to be felt more in a rest situation than a recumbent position (Griffin 1996).

It must also be recognized that vibration activity can affect the residential environment in a more or less permanent way, such as in the case of railway traffic, or may be transitory such as the vibration from construction sites. Therefore, this last characteristic has to be considered in the evaluation of the exposure. As well as potentially affecting the annoyance from vibration it also has major implications for the measurement of exposure. With permanent sources, like rail, it is possible to estimate exposure from internal measurements in the homes of survey respondents. On the other hand, this is not possible for transitory sources because of a logistical 'catch-22': the survey must precede measurements to avoid biased responses; however, the survey of annoyance must occur after the exposure and the measurement during the exposure. It is not possible to satisfy all these criteria simultaneously so large scale internal measurements are not possible for construction sites.

The evaluation of exposure is mainly done for each vibration source using a novel measurement methodology described in Technical Report 2. The exposure calculation relies mainly on two types of measurement:

- o Long term measurement
- o Short term measurement

Long term measurements, taken at 'control positions', are conducted close to the residential environment with the aim of capturing the full time history of the sources over at least an entire day. On the other hand, short term monitoring is used for evaluating the impact of the vibration activity within the respondent's property as close as possible the point of entry. The entire vibration activity, as monitored at the control position is then propagated into the respondent's property by calculation using the concept of the transfer function or velocity ratio (frequency dependent). In this way the entire full time history of the internal activity is provided and the exposure can be calculated using different metrics in order to evaluate which one is best correlated with the annoyance parameters as explained in the technical report number

six. The methodologies used for evaluating the exposure for each source are described in more detail in sections 3, 4 and 5.

The exposure felt by the residents inside their property is the product of a complex interaction of the vibration from the source to the receiver; therefore an evaluation of the uncertainty has to be done considering all the components of the measurement chain. The uncertainty evaluation depends on the measurement methodology and it is described in section 6. Conclusions are drawn in section 7.

2.2 STATE OF THE ART

The influence of vibrations on working and living environments has become an important problem in technologically advanced societies where requirements for environmental quality are becoming stricter and the environmental vibration that seemed to have been tolerated in the past is today increasingly being considered as a nuisance (H. Xia et al. 2005).

The human exposure to vibration inside the building is a quantity that can be determined by measurement or estimation. Generally, both Griffin (1996) and the Norwegian studies (Turunen-Rise et al. 2003) agree on the idea that the vibration exposure has to be measured or predicted in one position in one room. Standards encourage the assessment of the vibration exposure in mid-room or mid-span, the location that is both likely to represent the worst case. Some countries have their own approach to assessment and regulation of vibration in residential environments, for example:

- United Kingdom with BS 6472-1 (BSI 2008).
- United States with FTA guidelines (FTA 2006).
- Norway with NS 8176 (Norwegian Council for Building Standardization 1999) .
- Sweden with DNR.S02-4235/SA60 (Banverket 2002).
- Germany with DIN 4150-2 (Institute for German Standardization 1999).

Otherwise rules are sometimes adopted from guidelines provided either by institutions or other countries. The most significant guidelines related the evaluation of the human response in residential environments can be found in the following documents:

- ISO 2631-2 (ISO 2003)
- ANSI S3.29-1983 (R2001) (ANSI 2001)
- Nordtest Method NT ACOU-082 (Nordtest 1991)
- DIN 4150-2

A comprehensive comparison of the documents above can be found in appendix D of the TCRP Web-Only Document 48 (Zapfe et al. 2009) together with a list of national and international standards related to the evaluation of the human exposure to vibration in residential environments.

As previously stated, the United Kingdom has created its own guidance about human response to vibration in residential environments that can be found in BS 6472-1 (2008). The latter directs that vibration should generally be measured as acceleration. Unweighted (unfiltered) recorded time histories are preferred, from which any desired value can be obtained later. Measurements should normally be made on a building structural surface supporting a human body. In circumstances where this is not possible it is recognised that measurements may have to be made outside the structure or on a surface other than the point of entry into the human body. In those cases a transfer function to allow for the difference between the measurement point and point of entry to the body should be declared.

BS 6472 adopts a different exposure metric from those in the ISO, ANSI or DIN 4150-2 standards, namely the Vibration Dose Value $\left(VDV_{b/d,day/night}\right)$ defined as:

$$VDV_{b/d,day/night} = \left[\int_0^T a_w^4(t) \cdot dt \right]^{0.25} \qquad (1.1)$$

Where $a_w(t)$ is the frequency-weighted acceleration measured (in $m \cdot s^{-2}$), using W_b or W_d as appropriate; a T is the period (in s) during which vibration occur.

For describing random and continuous sources, the other standards are mainly oriented towards weighted energy average descriptors such as rms velocity or maximum rms values for specific events. For impulsive sources, peak particle velocity or acceleration is generally used. However, VDV is a descriptor that can be used for assessing vibration exposure for any type of vibration.

As well as codes of practice the literature includes studies of exposure and response to vibration. Several exposure response relationships have been derived for railway vibration. The more or less permanent nature of railways provides a repeatable and predictable vibration source which facilitates such studies. In the rest of Europe studies have been conducted for understanding the problem of the "human response to vibration" especially in Belgium, Holland (Ostendorf 2002) and in Scandinavian countries where problems with soft clay with high water content in densely populated areas cause vibration problems in dwellings from heavy road and rail traffic. Particular interesting are the study conducted by Klaeboe and Turunen-Rise et al. (Turunen-Rise et al. 2003) (Klæboe & Turunen-Rise 2003) (Klaeboe & Öhrström 2003) and the Swedish study TVANE project (Ogren & Ohstrom 2009) (Ohstrom et al. 2009) that investigate the effects of railway noise and vibration on sleep. Zapfe et al. (2009) have been conducted an investigation for deriving exposure response relationship for railway vibration in North America.

The differences between the study reported here and the studies cited above lies in the different determination of both response and exposure. In the other studies the response has been determined through telephone interviews whereas the determination of exposure has been done essentially on a sample of the population exposed to the vibration source relying on a few internal measurements supported by prediction methods. Further information about the different exposure-response studies for railway can be found in technical report 6. The methodology of the current study places more emphasis on intensive sampling of the exposure through internal measurements. In order to achieve the high sampling rates new measurement strategies have been developed (Woodcock et al. 2009).

Construction, as well as railways, can be considered an important source of vibration exposure in residential environments. However, compared with railways there have been relatively few exposure response studies for construction vibration. This probably reflects the far greater logistical difficulties in obtaining adequate sample size from transient sources. Construction activity has tended to be considered in relation to damage to buildings and settlement of soils especially when the energy level involved in the processes are high, as in the case of dynamic compaction and piling activity. However, an attempt to relate exposure and response to vibration in residential environments for construction vibration has been done in BS 5228-2:2009 annex B (BSI 2009) using PPV (Peak Particle Velocity) as descriptor for the exposure.

Internal activity or internal sources are defined in BS 6472 and are generally related to vibration generated by machines such as washing machines or human activity inside the building such as walking, slamming of doors or dancing. The structural characteristics of the building are important here, particularly in the case of tall, light structures as reported in the work of Sylvestre-Williams et al. (2010).

3 VIBRATION EXPOSURE FROM RAILWAYS

In this chapter the generation of railway vibration is first briefly reviewed after which the methodology for obtaining exposures from measured vibration is described.

3.1 VIBRATION CHARACTERISTICS

Railway vibration is a source that affects the residential environment externally as explained in section 2.1. It can helpfully be considered within the framework source-path-receiver. The mechanisms generating the vibration at source are complex and the product of the interaction of the source components:

- Train (carriage, wheel-axle, wheel)
- Track (track, sleepers)
- Sub Structure (ballast, embankment/cutting).

The weight of the train provides a basic stress field in the ground, while the unsprung mass and the suspension characteristics of the vehicles, together with their speed, will determine the extent to which track and rolling stock characteristics enhance this stress field (Dawn & Stanworth 1979). The vibration generated by the train-track interaction is generally mitigated by the structure underneath the rail, the ballast and embankment.

There are several mechanisms of generating ground vibration which may contribute to the total level of vibration in different frequency bands (Krylov 1996). Among these mechanism it worth mentioning the wheel-axle pressure on to the track, the effects of joints in unwelded rails, the unevenness of wheel or rails (all these mechanisms cause vibration at train-speed-dependent frequencies), dynamically induced forces of the carriage (such as bouncing, pitching and yawing) and wheel-axle bending vibrations excited mainly by unevenness of wheels and rails (these occur at their natural frequencies).

The most common generation mechanism is a pressure of wheel-axles onto the track (Krylov 1996). It is always present whereas all other mechanisms may theoretically be eliminated if rail and wheels could be made perfectly smooth and no carriage or wheel-axle-bending vibrations occur. In the ideal conditions described above, the wheel-axle pressure mechanism is probably a major contributor to train-speed-dependent components of the low frequency vibration spectra (up to 50 Hz), including the so called passage frequency $f_d = v/d$ where v is the speed of the train and d is the distance between the sleepers.

The dynamic excitations at the wheel-rail contact points come from the irregular vertical profiles of the wheel and the rail running surface. The variations in the

vertical profiles of either surface introduce a relative displacement input to the vehicle and track systems. A wavelength λ generates a frequency of excitation f=c/λ; where c denotes the train speed. For the frequency range of 5-80 Hz of interest for ground vibration and a train speed range of 36-250 *km/h* (10-70 *m/s*), the important wavelengths lie within the range of 0.125-14 *m* (Sheng et al. 2003).

Summarising, in the train there are some fixed lengths l_k such as the length of the train, the length of the car, the distance between the wheel, the distance between the sleepers, the distance between the bogies etc that when travelling at a speed v generate periodic vibration components with a fundamental frequency f_k according to:

$$f_k = \frac{v}{l_k} \tag{1.2}$$

The mass of the car on its suspension springs also causes a resonance frequency, typically of a few Hertz. In motion this generates an additional harmonic component due to pitching of the car. These oscillatory components belong to the quasi static contribution due to the moving load. On the other hand, the other sub-structure (ballast and embankment/cutting) can be also modelled as a mass spring damper system. If a resonance occurs with the train-wheel-track system, this will generate an amplification of the energy content in the band of the resonant frequency. Furthermore, all the complex mechanisms that generate the vibration (train-wheel-track-substructure) are purely mechanical and subjected to ageing over time such as unevenness of rail and wheels or the joint in unwelded tracks, introducing non linearity into the system. All these contributions belong to the dynamic load. Furthermore, we need to take in account the singularity in the railway track such as switch and crossing work, expansion joints, wheel burns on the rail, cable ducts beneath the track and many other that will increase the level of complexity of the vibration generation. Both quasi static and dynamic loads contribute to the randomness of the vibration source in a broadband of frequency range inside the physical human perception.

When the speed of the train is less than the Rayleigh waves speed in the ground (which will generally be the case in residential environments) the dynamic mechanisms of vibration generation are more important than the quasi static ones (Sheng et al. 2003 and Lombaert & Degrande 2009).

Generally, the system train-wheel-track system can be seen as an incoherent line source of vibration. According to Gutowski & Dym (1976), it is reasonable to simulate the passage of the train by using a moving line load, provided that the receiver, i.e., the point of observation, is in the far field of the source but at a distance

of less than $1/\pi$ times the length of the train. This approach is similar to the problem of sound propagation (Rathe 1969).

Madshus et al. (1996) investigated whether a train is a point source or a line source. Measurements performed by NGI[1] indicate that, for low frequency, the vibrations generated by a train are incoherent, if measured at a larger spacing than about 20 *m* along the track. Therefore, the train should be modelled as a series of statistically independent sources. The variance of the vibration from the whole train should be the sum of the variance from each car, making the train something between a point source and line source. According to Madshus et al. (1996), the main contribution to the near field of the source is given by the dynamic load. Furthermore, in the near field of the source the propagation modes of the vibration in to the ground are not completely developed making the vibration prediction difficult.

The vibration generated from the source with the mechanism explained above will mainly generate surface waves in the form of Rayleigh waves through the ground (Nelson 1987).

Once vibration is generated in the ground it will generally be attenuated or amplified during its propagation through the ground and into the building before being perceived by the human body.

3.2   METHODOLOGY

Having briefly reviewed the mechanism by which vibration is generated by railways, we now consider the methodology by which vibration exposures were obtained.

Guidance for measuring and evaluating the human response to vibration in residential environment is provided by the British Standard BS 6472-1:2008 "Guide to evaluation of human exposure to vibration in buildings" with the objective to assess the likelihood of adverse comment.

According to BS 6472 the acceleration time history of the vibration activity needs to be recorded as close to the point of entry as possible implying that measurements should be taken inside residences if possible. Moreover, an accurate exposure measurement can be done only if the vibration activity in the residential environment is monitored for a sufficient time period. The latter is identified as 24 hours on the basis of the assessment of the exposure from noise (Crocker 2007). However, 24 hours measurements for each case study are not practical in a project where a large number of case studies have to be conducted. A novel measurement approach has therefore been developed in order to reconcile the conflicting requirements of the

---

[1] Norwegian Geotechnical Institute.

project for a large number of measurements and those of the standard for a satisfactory length of each measurement. The main features of the approach are as follows:

1. Long-term monitoring at an external position herein referred as the 'control position'. Where possible, the control position is located at a similar distance from the railway as the affected properties.
2. Synchronized short-term snapshot measurement taken in the respondent's dwelling as close the point of entry as possible.
3. Calculation of a control-to-internal velocity ratio (frequency dependent) from 1 and 2.
4. Calculation of long-term vibration exposure inside the dwelling from 1 and 3.

If the respondent is at home or does not agree to an internal measurement, an external measurement should be taken as close to the foundations of the house as possible, if the respondent allows doing so. If the respondent does not agree to any measurement close to the property or is not at home, the external measurement is taken on the street in the front or back of the property.

The calculation of the exposure is based on the concept that the entire activity recorded at the control position can be 'propagated' to the point of entry inside the property using the measured velocity ratio. The main assumption is that there is a fixed relationship over time and space between the signal measured at the control position and that at the point of entry. The validity of this assumption can be influenced by various factors:

1. As mentioned in section 3.1, a train travelling at a finite speed along a given length of track will generate a vibration signal characteristic of the train, track and speed. In general the dominant signal at each measurement position will not necessarily arise from passage over the same section of track. If the train is of uniform consist and is longer than any of the normal distances from the track for target properties aligned perpendicularly, there will be a degree of spatial averaging. On the other hand short trains, and trains of non-uniform consist will not produce the same effect.
2. There are often singularities or non-uniformities in the railway structure such as culverts, points etc (see section 3.1) that might affect the signal at one position to a greater extent than the other. This effect will be most likely if the two measurement positions are in a line parallel to the track.
3. In the near field of the vibration source (See section 3.1) waves in the ground are not fully developed and therefore measurement positions in this region could show greater spatial variations than outside the near field.

The influence of the factors listed above has been mitigated by choosing to keep the control position close to the properties in which exposure is to be estimated. In this

way the wave field affecting the control position is similar to that affecting the building. In the surveys, the assessed properties were within a 50 *m* radius of the control positions so as to "sample" the vibration originating from the same part of track as that affecting the properties. Regarding the length of trains, the shortest trains, typical commuter trains, have been estimated to have four carriages with an approximate length of 80 *m*. Since the length of the train is greater than the separation of the two measurement points the influence of shorter trains should be minimised. It should be noted that the 50 *m* separation would sometimes be perpendicular to the track in which case both positions would receive signals from the same section of track.

The methodology presented above therefore provides an approximation of the 24 hour acceleration time history suitable for evaluation of the vibration exposure at the point of entry.

3.3 ANALYSIS

This section describes the analysis of the vibration measurement data and how this analysis results in the determination of the human exposure to vibration within a dwelling based on the measurement methodology summarized in the previous section.

The data for each case study is imported into Matlab and, using metadata contained in the *.gcf* files, information relating to each data stream is automatically acquired (i.e. which component the data represent, from which accelerometer the data were acquired, etc.). Events are identified in the Z-direction control position time history data via a process based on a STA/LTA[2] algorithm (see section 3.3.1) and a control to internal/external velocity ratio for each component is calculated for each event (see section 3.3.2). The velocity ratio for each event is linearly averaged to determine an average velocity ratio for the case study under analysis. The average velocity ratio for a case study can then be used to scale the long-term data measured at the control position to predict vibration within a property (see section 3.3.3).

3.3.1 EVENT IDENTIFICATION & EXTRACTION

Due to the large volume of data that will be generated by this project, manual detection of events would be a laborious task. STA/LTA is a triggering algorithm commonly used in seismology to detect seismic events and is defined as the ratio *R* between short-term average and long-term average of a time history:

---

[2] Short Term Average/Long Term Average

NANR209 Technical report 3

$$R = \frac{\frac{1}{sta}\sum_{p=1}^{sta} x_p^2}{\frac{1}{lta}\sum_{q=1}^{lta} x_q^2} \qquad (1.3)$$

Where x_n is a time history sta and lta are the width of the short and long time windows respectively.

An event is defined when the ratio R exceeds a defined threshold. The purpose of taking the short term average is to reduce the probability of triggering on short duration transients (such as footsteps) which is likely to occur if a trigger is used based directly on signal amplitude. The purpose of the long-term average is to provide a measure of the variation of the background noise. Setting the parameters for the sta and lta time windows and the R threshold is somewhat a matter of trial and error; for the detection of train passes it has been found that the following parameters are effective: sta = 1 s, lta = 15 s, and a threshold of around 80%. Once the algorithm has detected an event, a post- and pre-trigger of 10 seconds is applied.

The STA/LTA algorithm has been implemented in Matlab and picks events (i.e. train passes) with a success rate of around 80%. Although the event identification algorithm rejects short-term transients, it has been found that clusters of short-term transients (such as 30 s of footfalls) cause the algorithm to trigger falsely; events such as this make up the 20% of spurious triggers. In an effort to reject false triggers, discrimination based on crest factor has been employed. Crest factor is defined as the ratio between the peak amplitude and rms of a waveform:

$$C_n = \frac{|x_{peak}|}{x_{rms}} \qquad (1.4)$$

Short, highly impulsive signals will result in a high crest factor whereas waveforms with an amplitude envelope that develops slowly over time will exhibit a low crest factor. It has been observed that the vibration measured due to the passage of a train generally has a crest factor lower than 10; by rejecting triggered events with a crest factor higher than 10, the event identification algorithm made by the STA/LTA algorithm with the crest factor discrimination triggers to an extremely high accuracy quantified in 70%.

Furthermore, an integrity check has been conducted by manually checking the triggered events and rejecting contaminated data.

3.3.2 VELOCITY RATIO

As the internal and external measurements of vibration are synchronised in time with the twenty-four hours control position measurement, it is possible to calculate velocity ratios for each event recorded during an internal or external measurement. For the velocity ratios used in the study for evaluating the long term vibration exposure, time histories of events identified with the STA/LTA algorithm are converted to the frequency domain using a sliding window FFT (a 200 point Hanning window with 50% overlap in order to obtain a spectral resolution of 1 *Hz*) from which the magnitudes of the windowed sections are linearly averaged. Velocity ratios are then calculated using the following equation:

$$H(f) = \frac{|B(f)|}{|A(f)|} \qquad (1.5)$$

Where $|B(f)|$ is the averaged Fourier magnitude spectrum of an internal event or external event $|A(f)|$ is the averaged Fourier magnitude spectrum of an event at the control position. For each case study, an average velocity ratio is calculated by linearly averaging the velocity ratios calculated for each event.

$$H_{ave}(f) = \tfrac{1}{N} \sum_{i=1}^{N} H_i(f) \qquad (1.6)$$

Where N is the number of events recorded for each case study. A minimum number of 5 train passages are enough for obtaining a reliable velocity ratio. All the velocity ratios have been evaluated with zero phase differences.

3.3.3 PREDICTION OF EXPOSURE

In this section the prediction of the exposure from railway vibration is calculated in the following cases:

- Internal Measurement
- External Measurement
- No Measurement

In the derivation of the exposure-response relationship only the internal and no measurement cases have been considered. The reason is given by the main aim of the study itself that is oriented in the determination of an exposure response relationship for internal vibration especially for the railway vibration. The high success rate of internal measurement, around 56%, has permitted a good "sampling" of the internal

vibration activity in all the measurement sites. Furthermore, the measurement methodology together with the site configuration allow an estimation of the internal measurement based on similarity assumption as described in section 3.3.3.3.

In addition to descriptors for 24-hours vibration exposure, the exposure has also been calculated for the day (7:00 – 19:00), evening (19:00 – 23:00), and night periods (23:00 – 7:00).

3.3.3.1 Internal Measurement

An average velocity ratio is calculated for each case study by linearly averaging the velocity ratios calculated for each individual event according with the method outlined in section 3.3.2.

In order to predict internal vibration, the average velocity ratio for a case study is interpolated to the length of each individual event recorded at the control position. The velocity ratio is then applied to the complex Fourier spectrum of the event:

$$B_{pred}(f) = H_{ave} \cdot A(f) \qquad (1.7)$$

where $B_{pred}(f)$ is the predicted complex Fourier spectrum of an internal event, H_{ave} is the average interpolated velocity ratio calculated for that case study, and $A(f)$ is the measured complex Fourier spectrum of an event at the control position.

H_{ave} represents the energy ratio (frequency dependent) between the internal and the control position (1.6) used for scaling the spectral content of the event $A(f)$ in order to obtain the $B_{pred}(f)$ keeping the phase information of the event measured at the control position $A(f)$.

In this way the predicted spectrum $B_{pred}(f)$ is complex, it can be inverse Fourier transformed back to the time domain for the calculation of parameters such as peak, and VDV.

Equation (1.7) is repeated for each event recorded at the control position from which the entire 24 hours activity inside the respondent property can be predicted and therefore the vibration exposure caused by railway vibration.

The following figures show the prediction of internal events with the internal measurement at varying distances from the control position (10 *m*, 50 *m*, and 100 *m* respectively) both in the time and frequency domain. It can be seen from these figures that a good prediction can be achieved using this method. The tables below these figures show measured and predicted single figure vibration exposure descriptors (peak, rms, VDV).

NANR209 Technical report 3
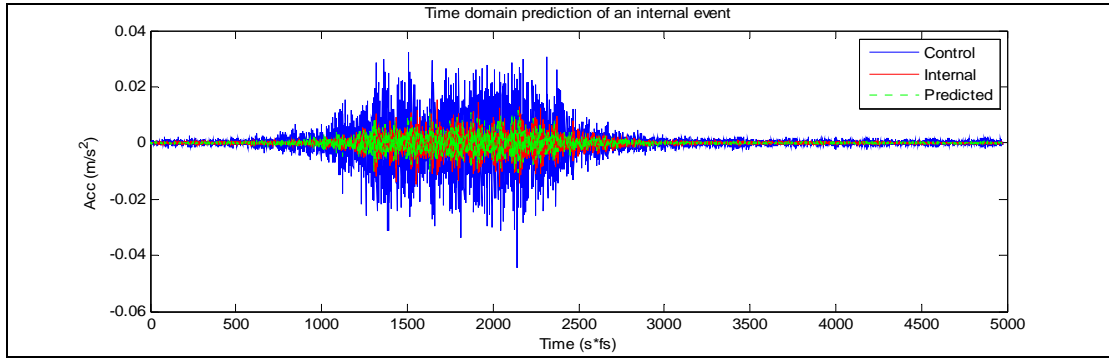
Figure 1 Prediction of an internal event around 10 *m* from the control position (time domain)
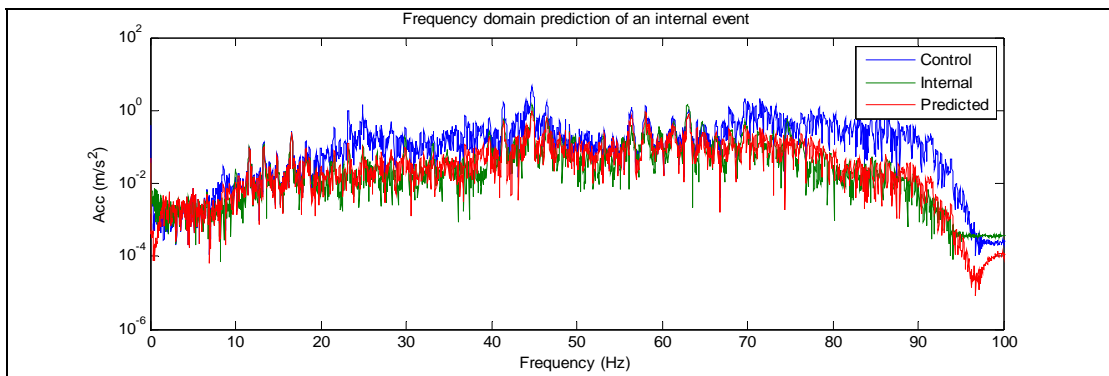
Figure 2 Prediction of internal measurement at 10 *m* from the control position (frequency domain)

	Measured	Predicted
Peak Particle Acceleration [m/s^2]	0.015	0.012
Rms Acceleration [m/s^2]	0.002	0.002
VDV [$m/s^{1.75}$]	0.033	0.026

Table 1 - Measured and predicted internal vibration exposure metrics at 10 *m* from the control position

NANR209 Technical report 3
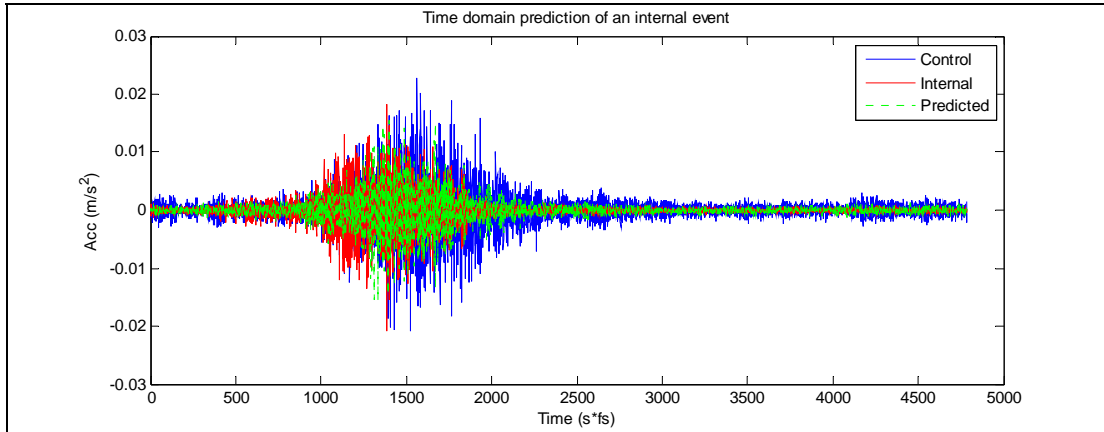
Figure 3 Prediction of internal measurement at 50 *m* from the control position (time domain)
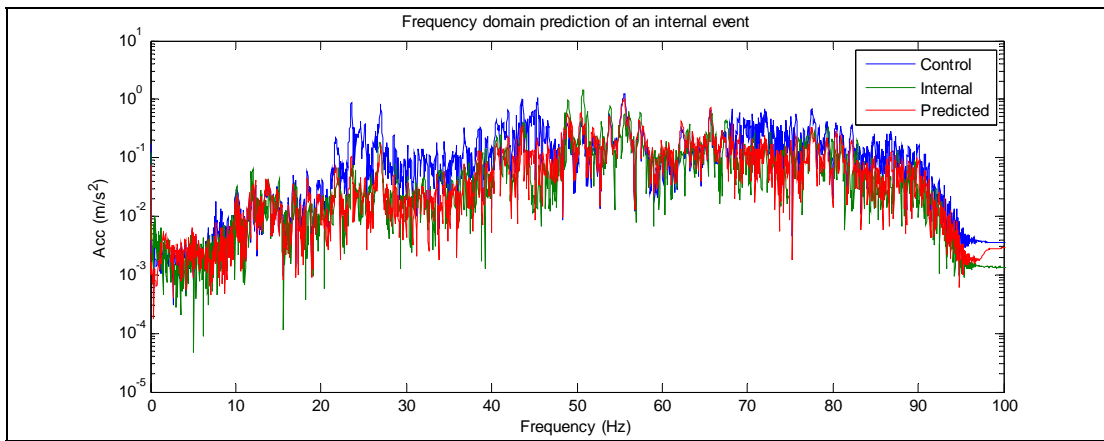
Figure 4 Prediction of internal measurement at 50 *m* from the control position (frequency domain)

	Measured	Predicted
Peak Particle Acceleration [m/s^2]	0.008	0.007
Rms Acceleration [m/s^2]	0.002	0.001
VDV [$m/s^{1.75}$]	0.023	0.018

Table 2 - Measured and predicted internal vibration exposure metrics at 50 *m* from the control position

Figure 5 Prediction of an internal event around 100 *m* from the control position (time domain)
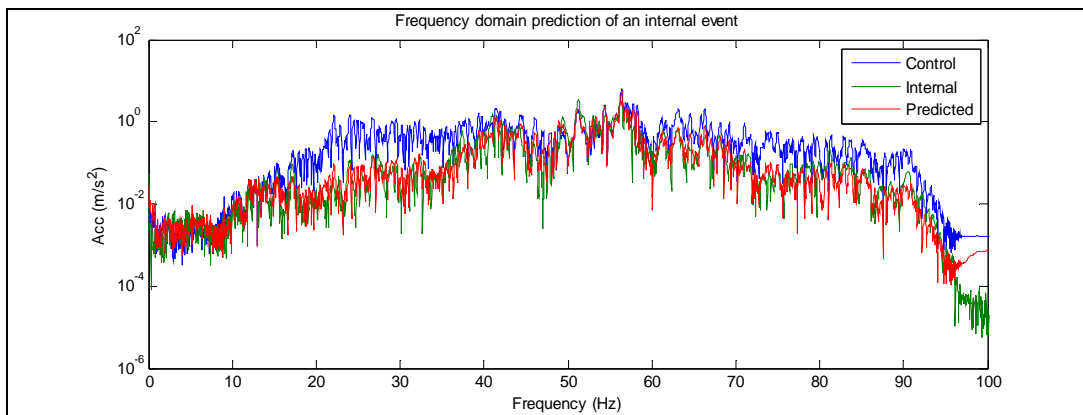
Figure 6 Prediction of an internal event around 100 *m* from the control position (frequency domain)

	Measured	Predicted
Peak Particle Acceleration [m/s^2]	0.053	0.050
Rms Acceleration [m/s^2]	0.006	0.007
VDV [$m/s^{1.75}$]	0.106	0.107

Table 3 - Measured and predicted internal vibration exposure metrics at 100 *m* from the control position

3.3.3.2 External Measurement

When a measurement is taken externally to the respondent's house the prediction of the exposure at the measurement point is done using the same approach for the prediction of the internal with the difference that in the formula (1.7) the average velocity ratio calculated for the case study is obtained by linearly averaging the velocity ratio between the external position and the control.

3.3.3.3 No Measurement.

If there is no internal measurement available for a given respondent, a search is conducted within the same area for a property of a similar type and a similar distance from the source within the site where an exposure measurement has been taken. The exposure estimated for this property is then assigned to the property for which there was no measurement available. All the properties are in a radius of 50 *m* from the control position in the measurement site, so the hypothesis of similarity between the properties is well supported in reality. The similarity for distance from the source can be found in the majority of the configuration of the measurement site where the line of the houses is parallel to the railway line.

4 VIBRATION EXPOSURE FROM CONSTRUCTION

In this chapter we briefly review construction activity as a source of vibration. We then proceed to describe the construction sites studied and the approach adopted for estimation of the exposures. It will be seen that, whereas intensive measurement of internal vibration was possible in the case of railways, the same approach cannot be adopted for construction sites. Instead, it is necessary to rely more on a few sample measurements supported by prediction models for propagation of the measured exposure to residences at different distances from the site. The prediction models are described, together with the procedure for obtaining the soil propagation properties from measurements obtained using an array of accelerometers. Finally, the curves derived for prediction of the exposure are described.

4.1 REVIEW OF CONSTRUCTION VIBRATION

Construction vibration affects the residential environment externally as defined in section 2.1. Vibration activity from construction consists of different sources depending on the operations involved on the construction site. According to Wiss (1981) all categories of vibration are generated from construction activity:

- Transitory or impact.
- Steady state or continuous.
- Pseudo-steady state or random.

Impact vibrations may occur from blasting or impact pile driving. Steady state vibration may be generated by vibratory pile driving and ground compaction by vibratory rollers. Pseudo-steady state or random vibrations may be caused by many small impacts at short intervals approaching a steady state condition, for example as caused by pavement breakers, trucks and bulldozers.

The energy of the sources involved in construction activities can be spread over several orders of magnitude as shown in Figure 7 explaining that construction activity can be a matter of concern not only for human response but also in relation to building damage and soil settlement.

The construction sources considered in this study are the following:

- Impact and vibratory pile driving.
- Pavement breaking/Shallow excavation.
- Compaction.
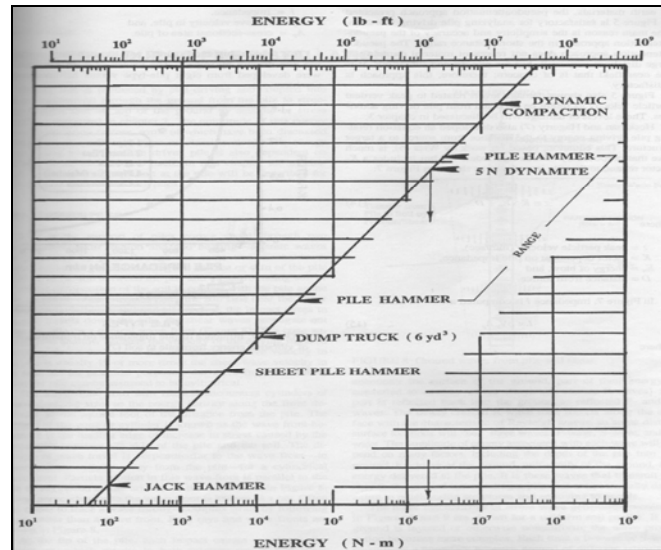
Figure 7 – Relative energy of various construction operations (Woods 1997)

Sources of construction vibration generate compression, shear and Rayleigh waves (Richart et al. 1970) in homogenous ground but they may also generate Lamb, Love and Stoneley waves in layered ground. However, Rayleigh waves have the largest interest in the evaluation of the human response because building foundations are placed near the ground surface. Furthermore Rayleigh waves contain roughly 70 % of the total vibration energy and become predominant over the other wave types at comparatively small distances from the vibration sources. For example, driven piles at depths of between 4 and 10 m will generate Rayleigh waves within 0.4 to 3 m of the pile, depending on the propagation of Rayleigh and compression waves (Svinkin 1999).

Various factors make the propagation of vibration a complicated phenomenon, for example the fact that high frequency components of vibration are attenuated faster than low frequency components. The propagation pattern is further complicated close to the source, in the so called 'near field' region, where non-linear effects may occur. The effect of soil strata heterogeneity and uncertainties in the geological profile should also be taken in account (Svinkin 2002). On entering the building, vibration levels may be amplified by resonance phenomena when the natural frequency of building elements corresponds to that of the exciting frequency.

It is common practice to assess the impact of construction vibration in terms of Peak Particle Velocity. This approach can be found for example in the works of Clough & Chameau (1980), Woods (1997), Athanasopouls & Pelekis (2000) especially with regards to vibration from pile driving. A description for the evaluation of the human response from construction is given in Wiss (1981) and in the book of Dowding (1996).

As explained in section 2.1 the assessment of human exposure to vibration needs to account for the duration of the vibration events. Figure 8 is based on the study of J. Wiss & Parmele (1974) on the perception of transient vibration, it shows that the levels of perception of the vibration can change with the exposure time, for example the barely noticed level decreases from 2.5 to 0.5 *mm/s* when the time of exposure increases from 1 to 100 *s*.
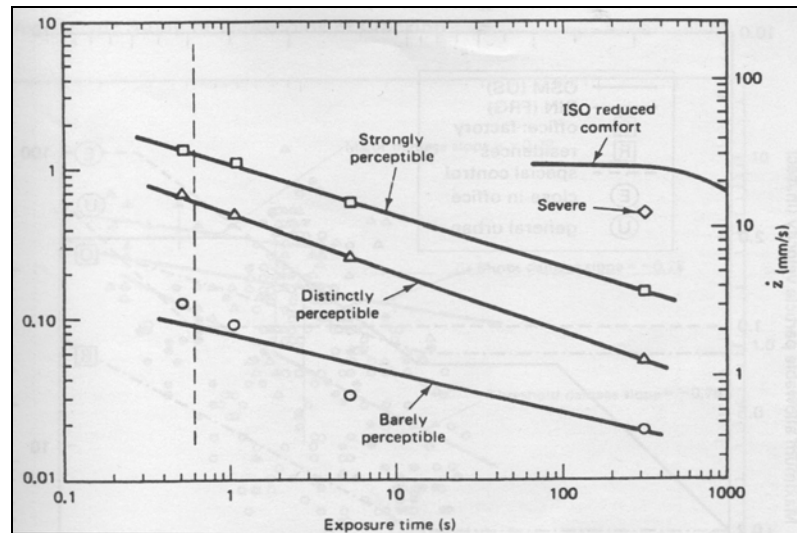
Figure 8 – Human response to transient pulses of varying durations (Woods 1997)

4.2 METHODOLOGY

As described in Technical Report 2, in the case of railways it was possible to conduct intensive internal measurements. However, the same approach cannot be adopted for construction sites because the transient nature of the work causes a logistical 'catch 22' situation: the social survey must be conducted before the vibration measurements in order to avoid biased responses, but for transient sources this must take place after the exposure has occurred by which time, the source of vibration has already moved on and internal measurements are no longer possible.

A different approach is therefore necessary for construction vibration which relies more on the prediction of vibration. As described in Technical Report 1, sites had to be selected with a sufficient population density to yield responses from several hundred residents but where it was also feasible to conduct the necessary measurements. The construction sites chosen were of a light rail installation where construction activities move along the route as the work progresses. Essentially the same operations are carried out at every point on the line and the source of vibration moves as sections are completed. This arrangement allowed us to take measurements on one part of the line and to assume that essentially the same exposure would occur

at other points on the line where surveys could take place independently of the measurements. Compared with the railway case, far more limited measurements were possible since any properties used for measurement could not be used for subsequent surveys without biasing the response.

Therefore, measurements were at a fixed location on one segment of the linear site and monitoring took place as the construction work passed by. The elements of the measurement approach are:

- Control position

- Internal position

- External array.

The purpose of the control position is to capture the entire life cycle of the vibration exposure from the various construction activities as they pass the measurement location. The control positions were established in a similar way to those for railway but monitoring occurred over a much longer period of weeks rather than 24 hours as used for railways. As with railways the internal measurement was carried out over a short period with the aim of establishing external-to-internal velocity ratios. The external array was a new element introduced so as to enable simultaneous measurements of the vibration at various distances from the source. From these measurements it is possible to evaluate properties of the soil and thereby to obtain a prediction of the exposure at any distance from the line. The development of the propagation prediction method is described in section 4.3.

The measurements were conducted on a part of the line where the major vibration activity had not yet occurred. Therefore, it was possible to monitor the whole evolution of the activity at the control position. Array and internal measurements were, of necessity, short term and were therefore timed by discussion with the construction manager to take place during the day of maximum activity. In this way the signal to noise ratios were as high as possible.

4.2.1 *DESCRIPTION OF MEASUREMENT SITES*
Figure 9 shows one of the sites used for assessing the exposure from construction activity. The site is for the construction of a new tramway and has the form of a 'linear' construction site where different construction operations occur, usually in sequence on different parts of the line according to the plan and the phase of the construction. Two such linear sites were used, referred to as Site A and Site B. Social surveys were conducted along the entire length of both sites but measurements were restricted to one section of the line. More detail for the measurement sites is given in Technical Report 1.

Site A

The measurement setup for site A is described in Figure 10. The aim of the works in site A was the reconversion of an old railway line to a light rail line. The major parts of the operation were carried out inside the cut where the old track was laid. In this scenario the operation from both impact and vibratory pile driving were measured for the installation of trackside structure. Seven metre tubular piles where driven into the soil along both side of the track at 25 *m* centres.

Figure 9 - Construction Site A

NANR209 Technical report 3
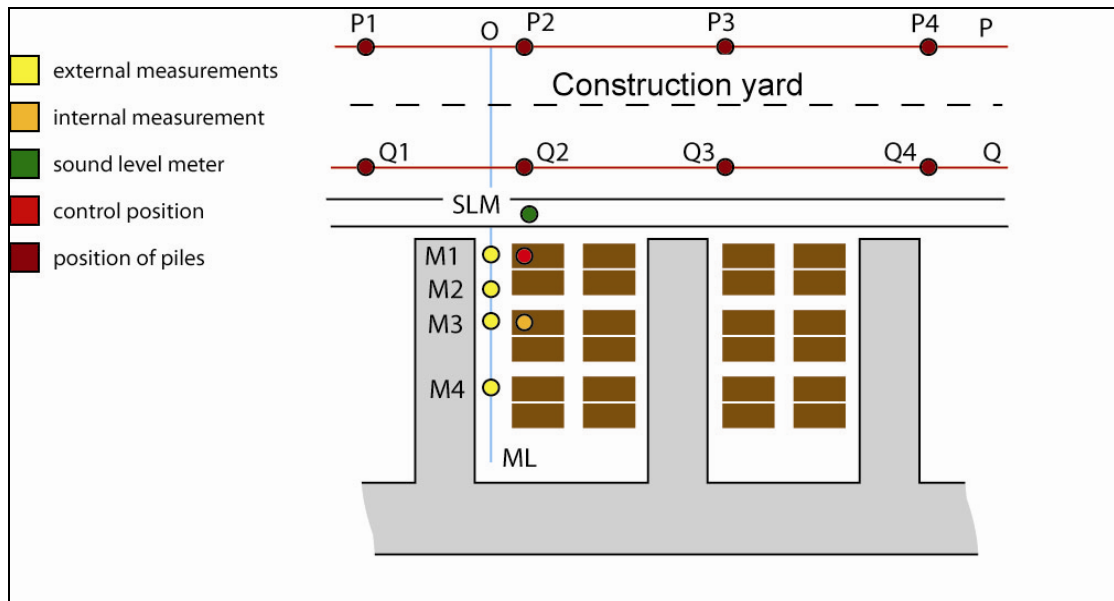
Figure 10 - Measurement setup for Site A

The line of the piles P and Q were situated 6.5 *m* from the centre of the track. The line of the piles Q is taken as the origin of the reference system. From there the distance to the control position is 6 *m*. The first transducer of the array, denoted M_1, was placed in line with the control position with the other transducers at 10, 20 and 40 *m* from the first element.

Taking the measurement line ML as a datum perpendicular to the track, the piles P1, P2, P3 and P4 are at distances of -15, 10, 35 and 60 *m* from O respectively.

Because the piling is a localised source it is also important to estimate the distances from the each pile (P1-4) to each point on the measurement array (M1-4). The distances from the pile $P_i \quad i = 1 \mathrm{K} \, 4$ and the measurement points $M_i \quad i = 1 \mathrm{K} \, 4$ form the hypotenuse of the triangles $\hat{P}_i O m_j \quad i, j = 1 \mathrm{K} \, 4$ which can be evaluated with Pythagoras's Theorem. The resulting distances are summarized in Table 4

NANR209 Technical report 3

	P1	P2	P3	P4
M1	24	21	40	63
M2	33	31	45	67
M3	42	40	52	72
M4	61	60	69	84

Table 4 – Site A distance between measurement position and pile position (Line P Figure 10) in meters.

Site B

At site B construction works have been carried out for a light rail installation in a residential street. A plan of the measurement layout is given in Figure 11. The works were carried out in strip approximately 100 *m* long and 8 *m* wide. The operations involved were:

1. Saw cutting
2. Pavement Breaking/Shallow excavation/Material Filling
3. Compaction
4. Slab and Rail installation
5. Tarmac covering

According to the construction manager, item 2 was most likely to be felt by the residents. However, the long term monitoring included items 1, 2 and 3.

There are significant differences between the construction activities carried out at Site A and Site B. At Site A the work consisted of a reconversion of the line and the works were carried out in an already existing installation in a typical and quiet residential environment reminiscent of those analyzed in the railway survey. The sources of vibration, piling, were well localized. Site B was a new installation carried out in a fairly busy main road where the construction operations caused disruption of traffic along the street. This situation may increase the background level of the vibration measurement. Unlike Site A, the vibration sources at Site B were not well localized and were continually moving although always within to the strip of land shown in Figure 11.
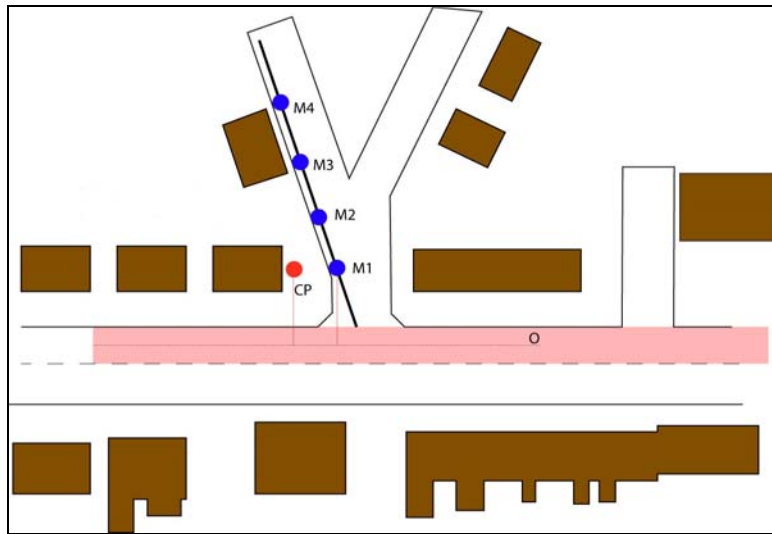
Figure 11 - Measurement setup for site B

In this case we define the datum line, O, at the centre line of the construction strip. The perpendicular distance between the reference system and the control position has been estimated as 14 *m* (Figure 11). As was the case for site A, the first element of the array was installed in line with the control position. The perpendicular distances with respect to the origin (line O in Figure 11) of the activity for the array elements are presented in Table 5.

M1	M2	M3	M4
14	23	32	42

Table 5 - Site B distance between measurement position and origin of the reference system.

4.2.2 *VIBRATION LIFE CYCLE*

Continuous records of vibration were made for 63 days at Site A and 36 days at Site B. The life cycle of the construction activity has then been analyzed by plotting the daily exposure recorded at the control position throughout the monitoring period. Event identification was first carried out manually from the time history in order to identify and remove vibration caused by any local human activity not related to the construction.

In Figure 12 is plotted the daily exposure between 08:00 and 18:00 at the control position for Site A expressed in terms of weighted peak particle acceleration (PPA) in the z direction, W_b. The maximum daily value is reached on the 21st day of monitoring with a maximum value of 0.2 m/s^2 recorded when a pile was driven at position Q2 very close to the control position (see Figure 10). On the other hand Figure 13 shows that the maximum of the W_b weighted PPA (z component) is reached at the 4th day of monitoring at Site B with 0.16 m/s^2 due to pavement breaking and shallow excavation. The second highest peak, occurring on the 32nd monitoring day, is probably due to compaction activity.
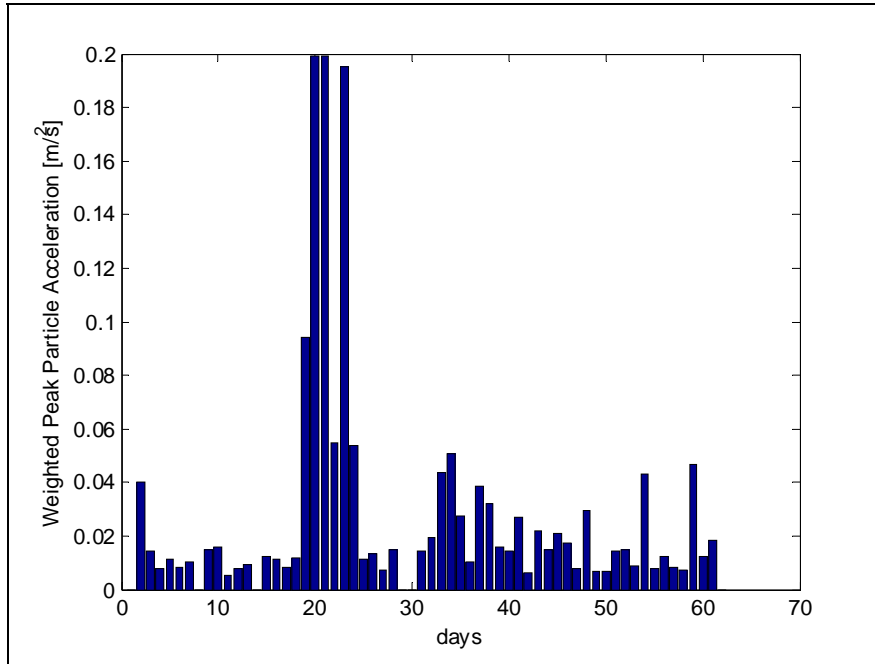
Figure 12 - Site A Weighted W$_b$ Peak Particle Acceleration (z component) over 10 hours vs monitoring days. Lifecycle of the construction activity.
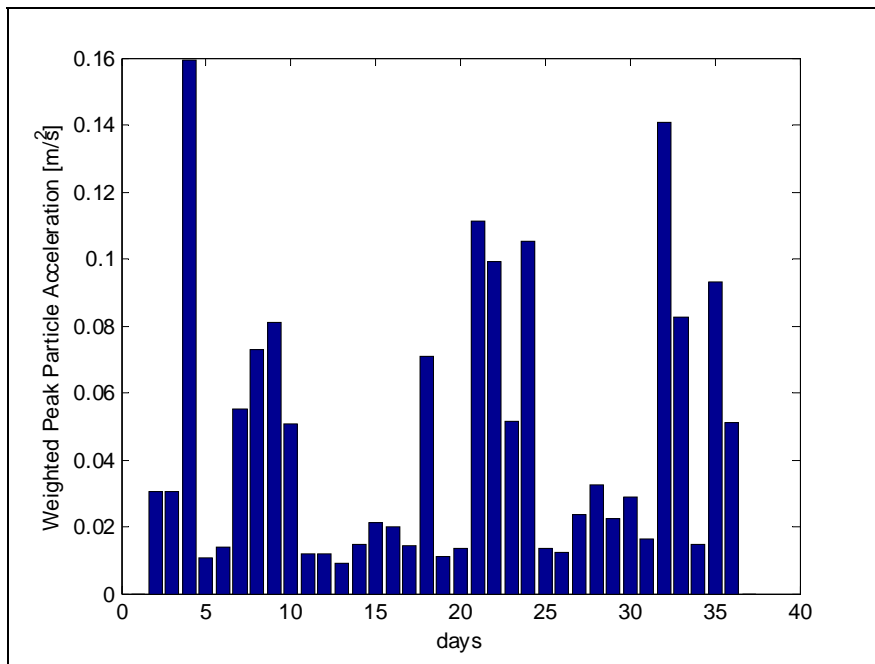
Figure 13 - Site B Weighted W$_b$ Peak Particle Acceleration (z component) over 10 hours vs monitoring days. Lifecycle of the construction activity.

4.3 MODELLING PROPAGATION

In this section the development of the method for predicting the vibration exposure at different distances from the construction site is described. The underlying theory and assumptions are first presented. The method of obtaining damping factors for the soil from the external array measurements is then described and the model validated. Finally, the propagation of vibration from the ground to the building is discussed.

4.3.1 BARKAN'S LAW

The main aim of the array measurements is to derive a propagation law for each measurement site using one of the semi empirical relationships presented in the literature. Examples of methods for predicting ground-borne vibration attenuation with distance for source specific construction operations can be found in BS 5882-2:2009 Table E.1 or R. Woods (1997) for pile driving. Those relationships can be applied only if a complete a set of parameters related to the source is known. This information is not available for either of the sites. Therefore, the most commonly used distance attenuation relationship in literature has been used, known as the Bornitz equation (R. Woods 1997), expressed as:

$$A(d) = A_0 \left(\frac{d_0}{d} \right)^n e^{-\alpha(d-d_0)} \tag{1.8}$$

The equation relates the magnitude of the acceleration A at a distance d to the level of the known acceleration A_0 at distance d_0 from the source. The geometrical attenuation parameter n and the material damping α need to be determined.

The geometrical attenuation parameter n depends on the wave type propagating through the soil. n is 1 for body waves, 2 for body waves at the surface and ½ for Rayleigh waves. As described earlier, it is assumed that the predominant wave type for construction vibration is Rayleigh waves and therefore we will assume n=1/2. The Bornitz equation with this assumption is known as the empirical relation called Barkan's Law (Barkan 1960).

$$A(d) = A_0 \sqrt{\frac{d_0}{d}} e^{-\alpha(d-d_0)} \tag{1.9}$$

α depends on the natural characteristics of the ground to attenuate seismic waves: softer materials generally have greater α values whereas harder materials have smaller values. In the case of steady state sources it is also possible to relate the α value to the soil characteristics using the classification proposed by R. D. Woods & Jadele (1985). The approach adopted here is to use Barkan's law to fit the

experimental data obtained from the external array and thereby obtain an empirical estimate for α for the specific site. The α -value obtained will then be substituted into Barkan's law yielding a model for prediction of the vibration magnitude at any distance.

In fact, in our experimental scenario many of the sources considered are not steady. We also must bear in mind that propagation in the residential environment does not conform to free field propagation because of the presence of scattering from the foundation of houses, pipes in the ground etc. Furthermore, the soil is likely to be layered and therefore not to conform to the idealized condition of an elastic half-space.

4.3.2 CALCULATION OF SOIL PROPERTIES

Figure 14 shows results obtained from the external array at Site A. The z component of Peak Particle Acceleration (PPA) is plotted against distance for times when piling was taking place at different pile positions (see Figure 10). It is noticeable that significantly lower levels are obtained for piling at P3 and P4. This is thought to be because these positions were shielded from the measurement array by a row of houses whose cellars were acting as wave barriers and therefore causing attenuation of vibration. According to R. Woods (1997) the barrier usually must be at least one wavelength deep in order to cause significant screening. Since Barkan's law assumes free field propagation only the contributions coming from P1 and P2 will be considered and P3 and P4 will be ignored for fitting of the attenuation parameter. The shielding effects are difficult to calculate but will be considered in the formulation of the uncertainty related to the exposure estimation. The fit of the experimental data with Barkan's law provides an α -value = 0.0250 for site A.

A similar analysis has been carried out for Site B (see Figure 16). It should be remembered that the vibration sources for Site B were far less localised than the piling operations at Site A and the houses did not have cellars, so the same issue of shielding did not arise. The data fitted with Barkan's law provide an α -value= 0.00379 for site B.

One can obtain an idea of the scatter likely to be obtained in the prediction on the two sites by considering the deviation of the measured points from the fitted curve in Figure 16. In addition, Figure 17 plots two decays for data obtained at different times of the day. A slight over-estimation is evident for distances greater than 30 *m* in one case but not the other. Generally, it is likely that the accuracy of the prediction will decrease at distances further from the source. In the case studies considered the range of distances goes from 10 to 220 *m*. On the basis of these results, Barkan's law provides a reasonable approximation of the propagation on soil for the sources considered in this study. However, a quantification of the daily variation of the

operation is needed for a better estimation of the uncertainty related to the prediction method.
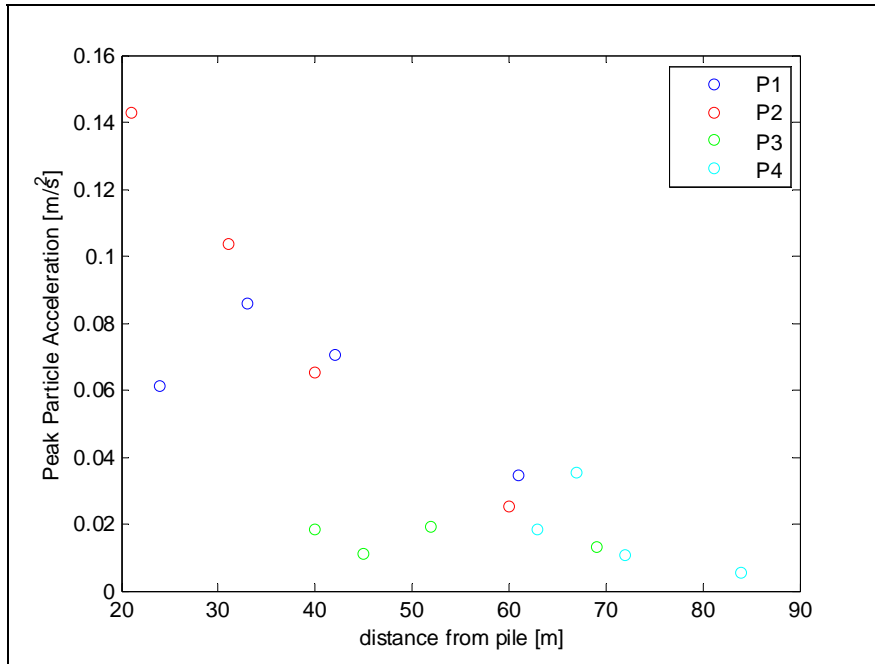
Figure 14 - Site A Peak Particle Acceleration (z component) vs distance from pile (table 4). P1 P2 P3 P4 pile positions (figure 10)
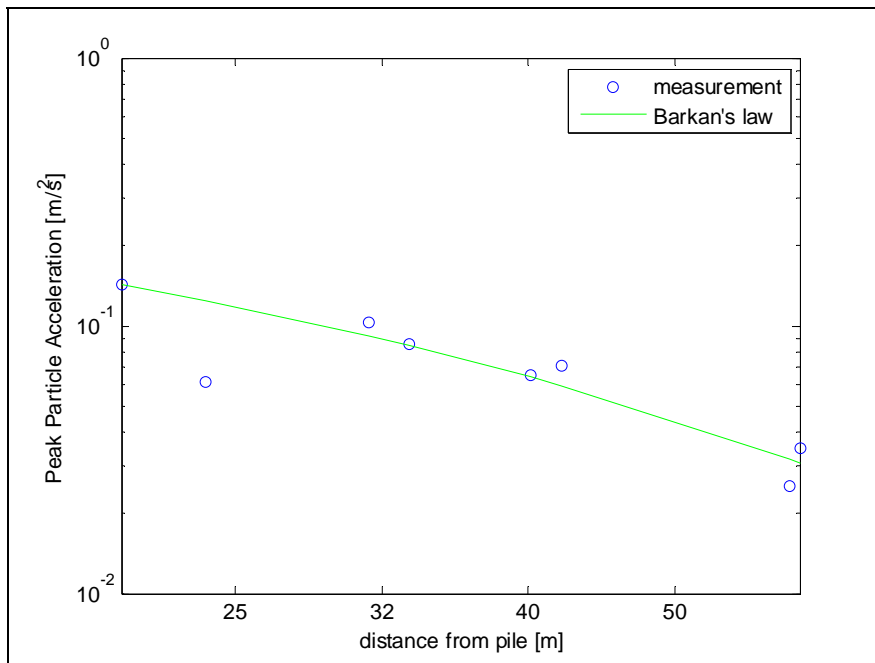
Figure 15 Site A Peak Particle Acceleration (z component) vs distance from pile (only contribution P1 and P2). Measured Point (dot) Experimental fit with Barkan's Law (line). Graph in logarithmic scale.
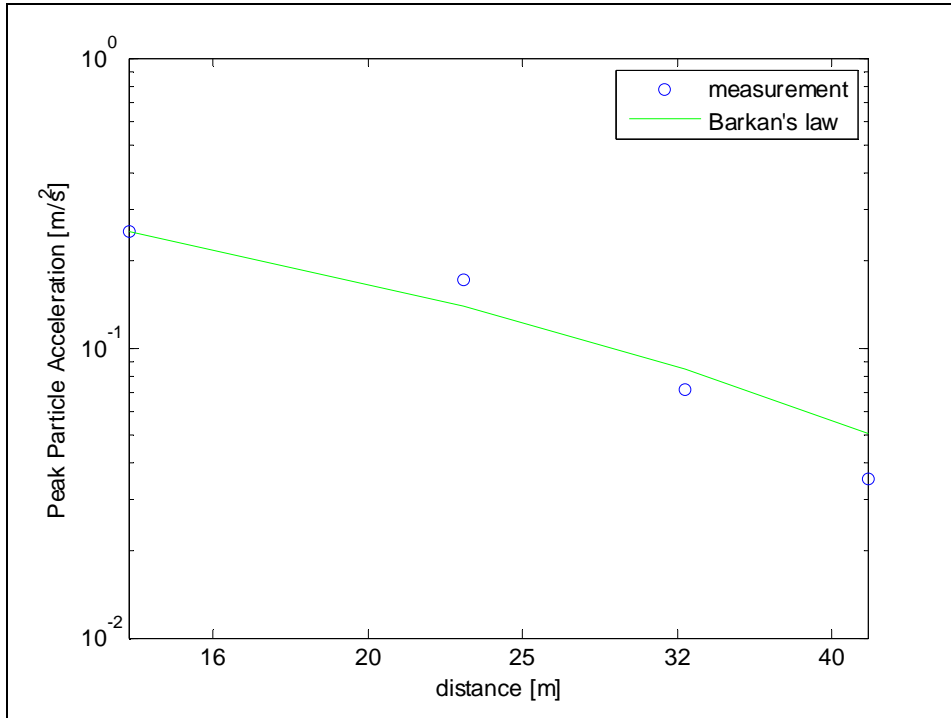
Figure 16 - Site B Peak Particle Acceleration (z component) vs perpendicular distance from the origin (figure 11)(table5) . Measured Point (dot) Experimental fit with Barkan's Law (line). Graph in logarithmic scale.

Figure 17 – Site B. External Weighted W_b Peak Particle Acceleration (z component) vs perpendicular distance from the origin (figure 11)(Table 5).Variability of construction operations at different times of the day. Measurement (dot) estimation with Barkan's Law (line). Graph in logarithmic scale.

Further insight into the reliability of the results can be gained by carrying out an octave band analysis as reported in the following paragraphs. The approach is essentially the same as that reported above but is carried out using vibration data that is pre-filtered in octave bands. In this way we should be able to quantify the frequency dependence of the material damping (Rix et al. 2000).

In Figure 18 and Figure 19 the estimated decays using Barkan's law from 4 to 64 *Hz* are presented for the vibration signal recorded in Site A and B. A strong dependence on frequency is evident. At site A the bands centred at 32 and 64 *Hz* are attenuated faster than for Site B. This difference can be assigned to the different nature of the soils at the two sites, but could also be affected by the level of background vibration especially at high frequencies. The material damping coefficients expressed in octave bands are presented in Table 6.

	4Hz	**8Hz**	**16Hz**	**32Hz**	**64Hz**
α Site A	0.0098	0.0254	0.0151	0.0676	0.12
α Site B	0.0043	0.0156	0.0313	0.0527	0.061

Table 6 - Site A Damping coefficient in octave band

The analysis of the damping coefficient at 4 *Hz* can give also an evaluation of the soil type by comparison with tabulated values (usually given at 5 *Hz*). According to the classification done by R. D. Woods & Jadele (1985) both the sites fall into class II soil types. The latter are also called *Competent Soils* that include sands, sandy clays, silty clays, gravel silts and weathered rock. This is a good description for the soil type in both measurements site and provides some indication that the curve fitting procedure is yielding reasonable values. A further confirmation about the soil type can be done only for Site A where borehole data are available.
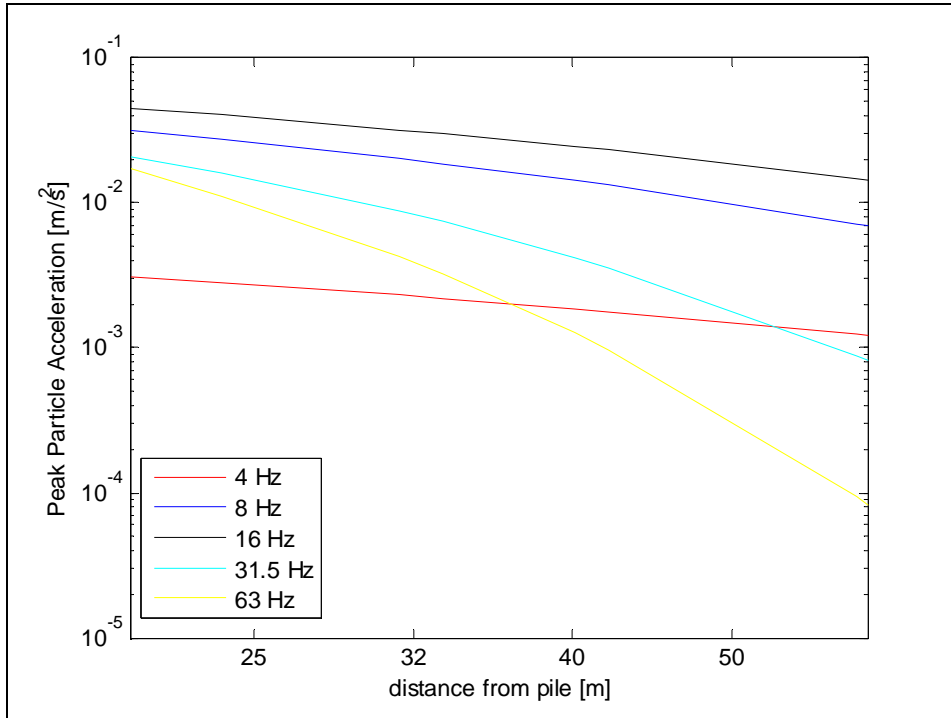
Figure 18 - Site A Peak Particle Acceleration (z component) vs distance from pile (Table 4). Estimated decay of the Peak Particle Acceleration expressed in Octave band centre frequencies (4Hz 8Hz 16Hz 31.5Hz and 63Hz) with Barkan's Law. Graph in logarithmic scale.
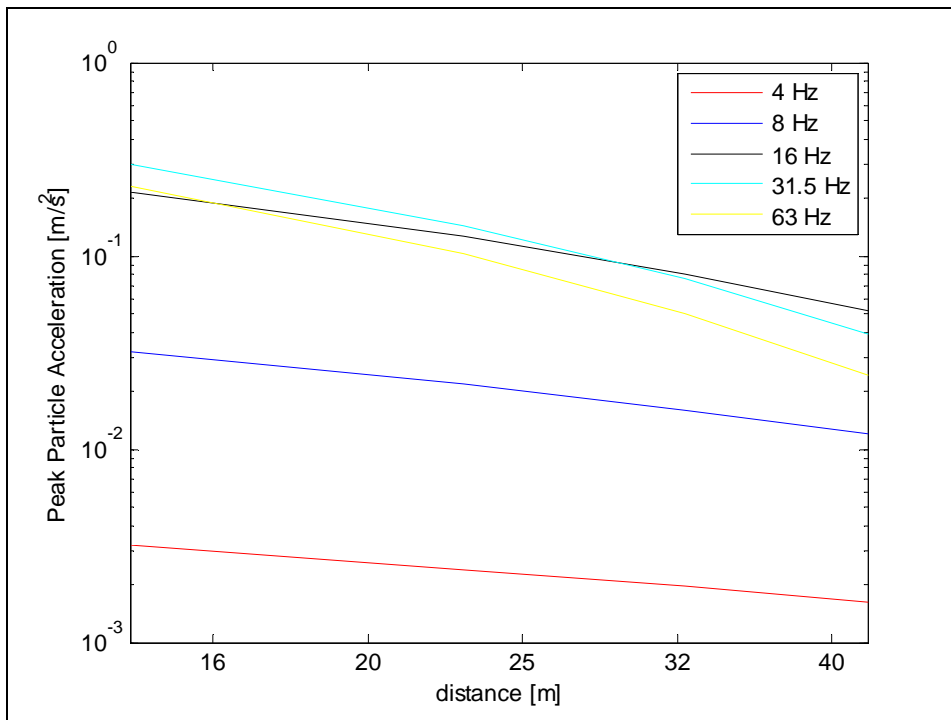
Figure 19 - Site B   Peak Particle Acceleration (z component) vs perpendicular distance from the origin (figure 11)(Table 5).Est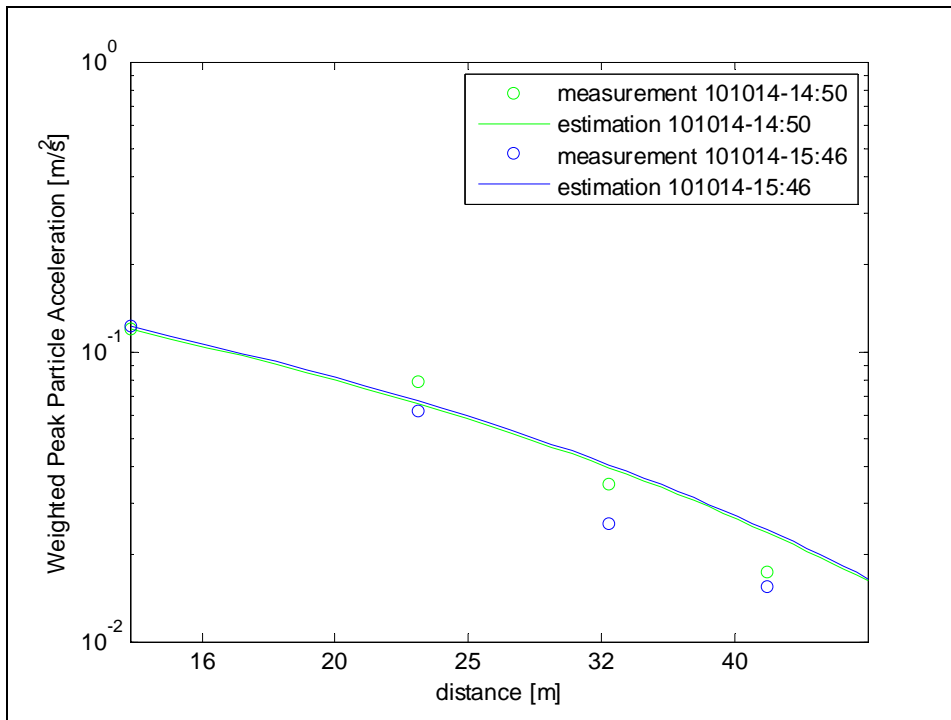imated decay of the Peak Particle Acceleration expressed in Octave band centre frequencies (4Hz 8Hz 16Hz 31.5Hz and 63Hz) with Barkan's Law. Graph in logarithmic scale.

4.3.3 *VALIDATION OF PROPAGATION MODEL*

In the previous section we have analyzed the propagation characteristics of the construction vibration using Barkan's law. The first step in the prediction of the exposure is to understand if the semi empirical relationship used in the controlled experiments can be also used for describing the propagation of the vibration metrics used for assessing the human exposure. The metrics considered in this case will be: weighted peak particle acceleration (PPA), weighted rms acceleration, VDV and weighted root mean quad (rmq) acceleration. The metrics are all calculated with respect to the z component of the acceleration applying the W_b.weighting.

For each metric M we have considered the formula:

$$M(d) = M_0 \sqrt{\frac{d_0}{d}} e^{-\alpha(d-d_0)} \qquad (1.10)$$

where $M(d)$ is the metric at distance d from the source and M_0 is the metric evaluated at d_0 from the source and α is an effective attenuation coefficient.

In Table 7 the result for the fit of the experimental data in Site A is presented showing that all the exposure metrics propagate in a similar way. Similar results have been found for the metrics in Site B and for the exposure metrics expressed in octave for both sites. It is reported in Technical Report 6 that the various metrics are all well correlated and the above results can be taken to confirm this.

Site A	W RMS	VDV	W PPA	W RMQ
α	0.017	0.018	0.021	0.02

Table 7 – Effective Attenuation Coefficient for Weigheted W_b (W) metrics

It has already be shown that Barkan's Law describes the propagation of the weighted W_b Peak Particle Acceleration quite well and together with the results shown above we can assume that this semi empirical relationship can be used also for describing the propagation of the other exposure metrics.

4.3.4 *PROPAGATION INTO BUILDINGS*

In the previous two sections the propagation of vibration through the ground was considered. In addition, if vibration exposure inside buildings is to be evaluated then it is necessary to account for transmission into the building from the ground. The approach is similar to that conducted for railways in that simultaneous internal and external measurements have been made which can be evaluated to give an external-to-internal velocity ratio. A difference from the railway survey is that only a small number of internal measurements have been taken for the construction sites.

The property type at site A in which internal measurement was taken is a semidetached house for which the frequency dependent external-to-internal ratio of weighted W_b PPA (z component) is shown in Figure 20. The measurement has been taken at the first floor in the centre of the room. At site B two property types have been considered: a terraced house (results in Figure 21) where measurements were made at the centre span of the ground floor living room and a semidetached house (Figure 22) where measurements were taken in the hallway at ground floor.

It can be seen that the octave band velocity ratios vary from about 0.6 to 4.2 with the higher values obtained for first floor and for measurements at the centre span of a larger floor. The numbers of measurements are too few to be confident about the values. In theory we could also use the velocity ratios obtained for the railway study for which many measurements were made but this will be left to future work.

The building responses presented here have been evaluated when the distance between the source and the building measured was a minimum: for site A (figure 10) this distance was 40 metres (Table 4 measurement position M3 pile position P2) whereas for site B it was 14 meters (Table 5). It is not known if the building response may change with the distance from the source or with the direction of the source.

A single figure amplification factor has been obtained as the ratio between the weighted W_b PPA measured internally and the one measured in the closest external measurement position. Results are shown in Table 8. These figures should be treated with some caution because they are based on only one property of each type.
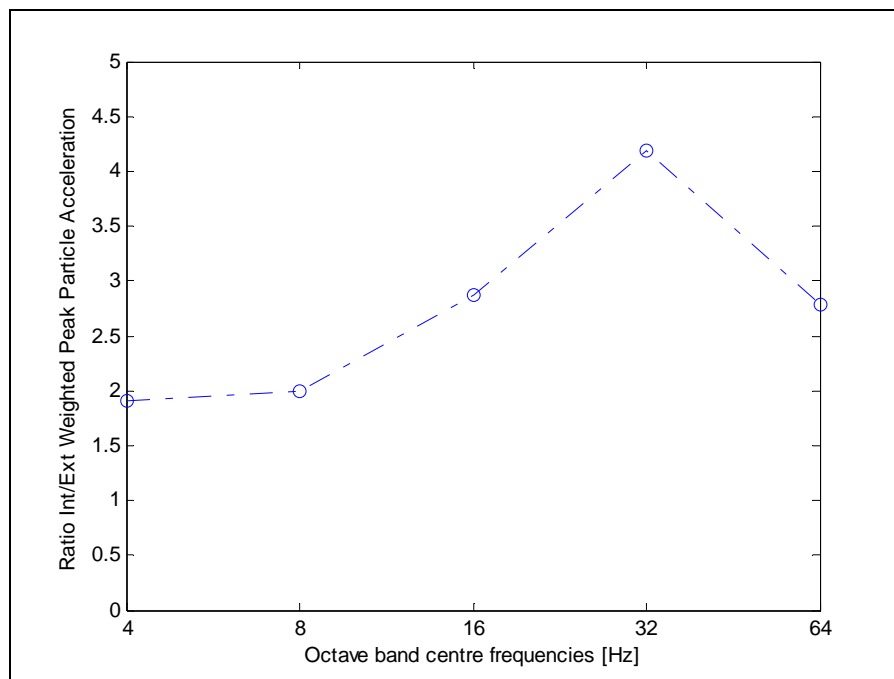
Figure 20 - Site A. Ratio Int/Ext weighted W_b Peak Particle Acceleration (z component) in Octave band. Building response semidetached house. Internal measurement at first floor in the mid-span.

NANR209 Technical report 3
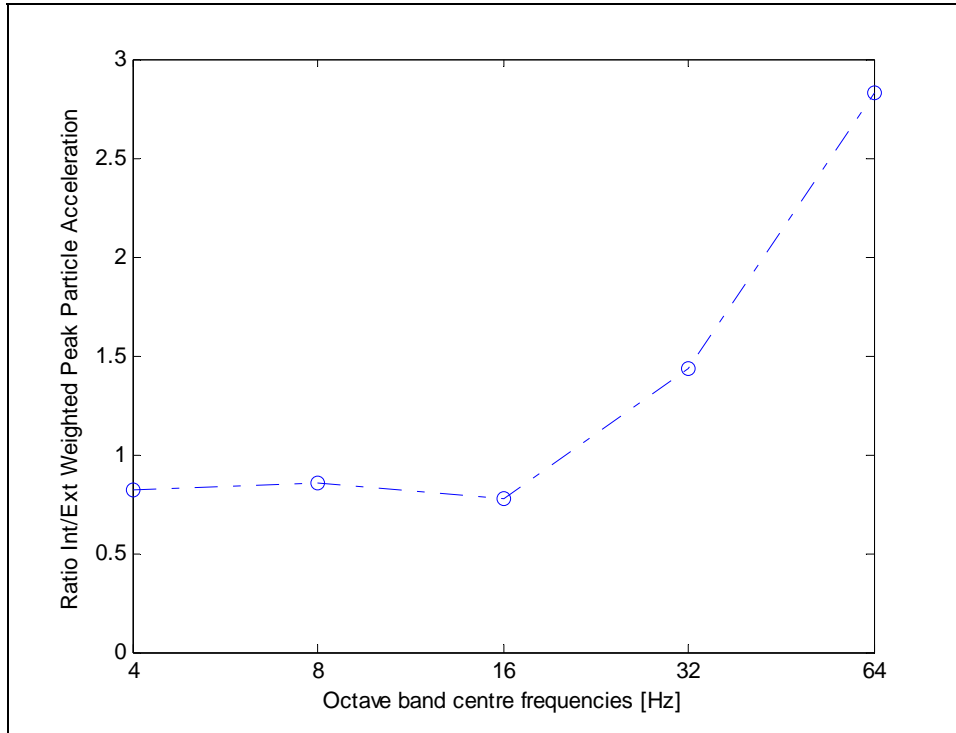
Figure 21 - Site B. Ratio Int/Ext weighted W_b Peak Particle Acceleration (z component) in Octave band. Building response terraced house. Internal measurement at ground floor in the mid-span.
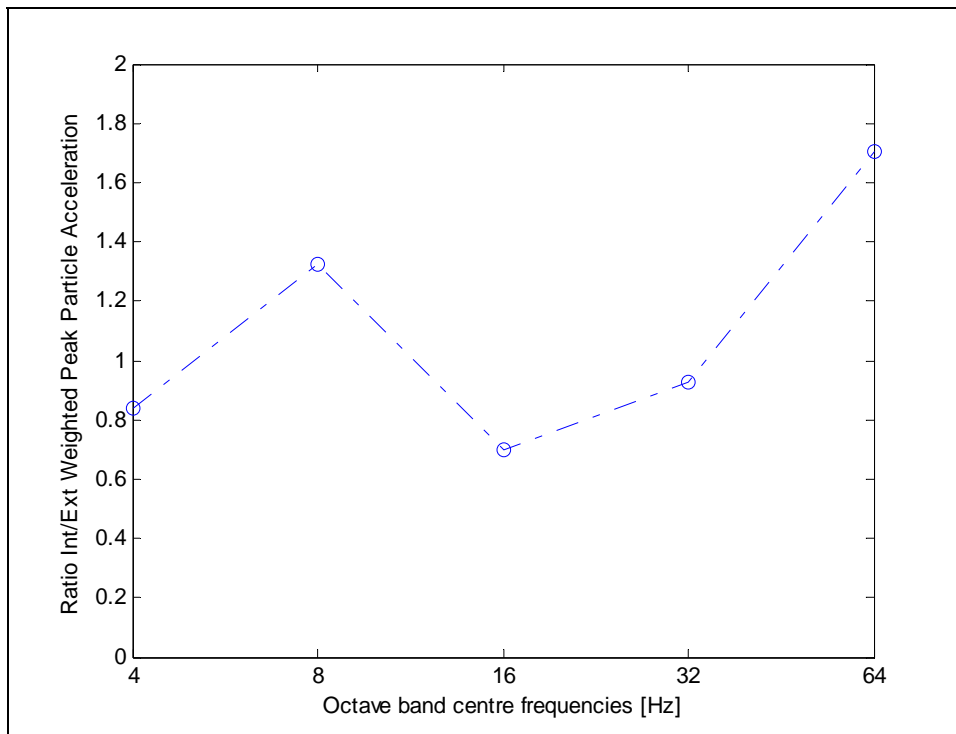
Figure 22 – Site B. Ratio Int/Ext weighted W_b Peak Particle Acceleration (z component) in Octave band. Building response semidetached house. Internal measurement at ground floor in the hallway.

NANR209 Technical report 3

Site	Property type	Amplification Factor
A	Semidetached (1st floor)	2.2
B	Terraced (g. floor)	0.6
B	Semidetached (g. floor)	0.4

Table 8 - Single figure Amplification factor for different property types

4.4 CALCULATION OF EXPOSURE

In order to calculate the daily exposure at different positions we start with the control position measurement which is considered an external measurement. The exposure metrics are calculated from the control position data and then propagated to the appropriate distance using Barkan's Law (with empirical attenuation parameters identified from the array measurements, section 4.3.1). If an internal exposure is required then it is necessary to apply the external-to-internal velocity ratios as described in section 4.3.4.

The exposure can be evaluated for the whole monitoring period or by just considering the combination of the maximum daily exposures caused by the set of operation involved in the construction processes.

It is important to test the representativeness of the control position for representing the vibration acting externally in the residential environment. This is important because the exposure found has to be representative of all the sites and not only for the measurement site. The experimental measurements for both the measurement sites shown in Figure 15 and Figure 16 have been considered.

In Figure 23 the external measured exposure from site A has been compared with the one propagated from the control position using equation (1.10) showing that the control position is a good predictor of the external vibration when the source is very close to the residential environment. The latter can be used for assessing the external vibration in the worst case scenario described above but an uncertainty has to be defined considering that the construction sources are moving. In fact in the case when the source is far from the control position a difference of a factor of 2 between the measurement and the prediction from the control position has been found for site B as shown in the Figure 24.

The methodology has been tested trying to reproduce two experimental situations where the internal exposure has been measured. In the first case we will predict the internal exposure measured in the property type of site A in the worst case scenario represented by the piling activity measured from position P2. The level of exposure

measured at the control position at 15 *m* is used for estimating the exposure inside the house at 35 *m* from the source. The results are shown in Table 9.

Site A	W RMS	VDV	W PPA	W RMQ
Measured	0.013	0.11	0.11	0.027
Predicted	0.019	0.15	0.15	0.039

Table 9 – Site A Prediction of internal Weighted W$_b$ (W) metrics comparison.
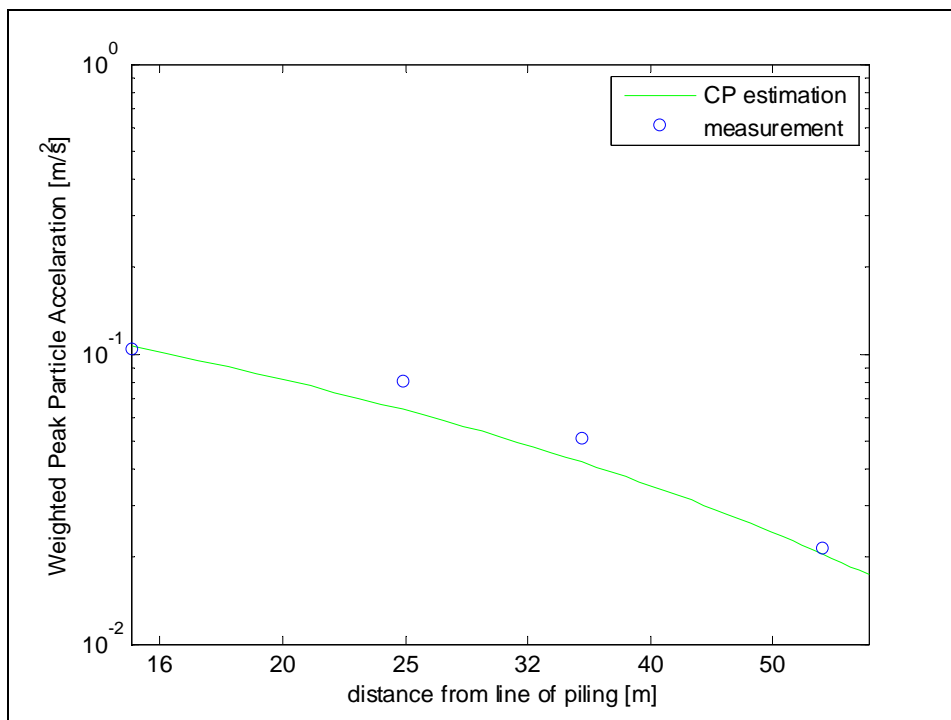
Figure 23 – Site A. Weighted W$_b$ Peak Particle Accelerationvs (z component) distance from the line of piling P (Figure 10). External weighted W$_b$ Peak article Acceleration measured (dot). Estimated External weighted W$_b$ Peak article Acceleration from the CP using the Barkan's law (line).

The second case we have considered an experimental situation encountered at site B. The internal vibration at 32 *m* from the source is predicted using the level of the exposure from the control position at 14 *m*. The amplification factor used in this case is the one for the terraced house. Results are shown in Table 10.

The same methodology can be applied for the estimation of the internal exposure in octave bands. Each metric in octave bands, using Barkan's law, is propagated from

the control position using the attenuation coefficients found in the controlled experiments. The internal exposure is obtained correcting the exposure level for each band by the building response as defined in the previous section.
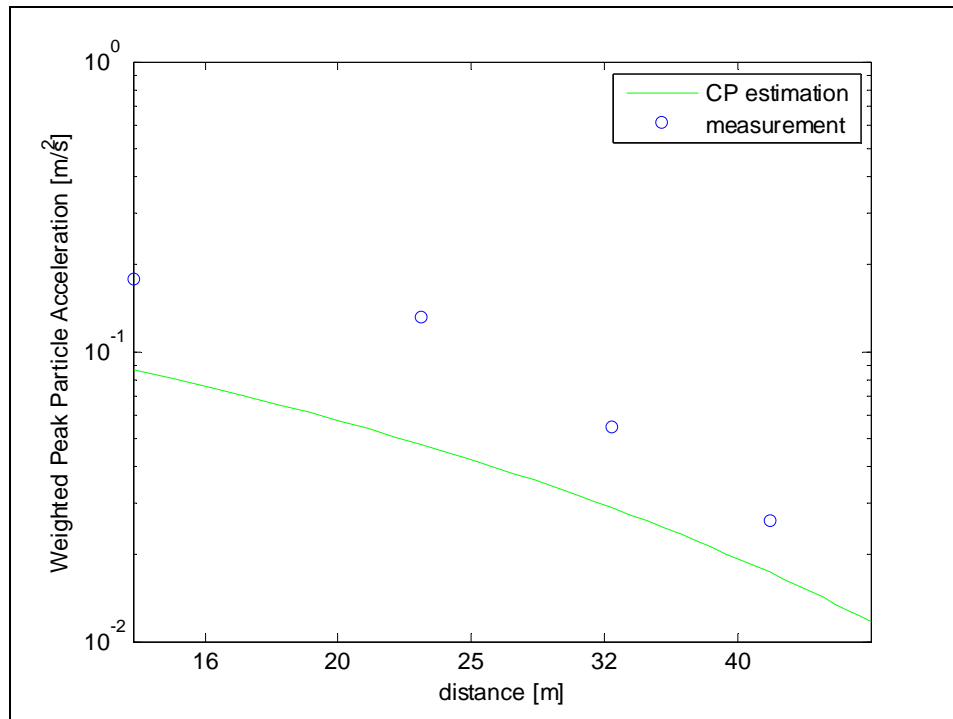
Figure 24 - Site B. W_b Weighted Peak Particle Acceleration (z component) vs distance from the line of the works (Figure 11). External weighted W_b Peak article Acceleration measured (dot). Estimated External weighted W_b Peak article Acceleration from the CP using the Barkan's law (line).

Site B	W RMS	VDV	W PPA	W RMQ
Measured	0.0023	0.067	0.11	0.0079
Predicted	0.0011	0.034	0.06	0.004

Table 10 – Site B Prediction of internal metrics comparison (W stands for W_b Weighting).

The prediction method has been tested with the same set of data used in the validation of the propagation of single figure metrics. The results of the prediction of the internal exposure expressed in weighted W_b Peak Particle Acceleration (z component) are presented in Figure 25 and Figure 26.

In the prediction of single figure internal metrics the methodology works better for site A where the estimation have been done on a piling source that is more narrowband in comparison of the activity for the other site where the nature of the

source is broadband. At site B an underestimation of the metrics has been found. The latter can be also assigned in the estimation of the building response using a different property type where the measurement position provided a better estimation of the exposure.
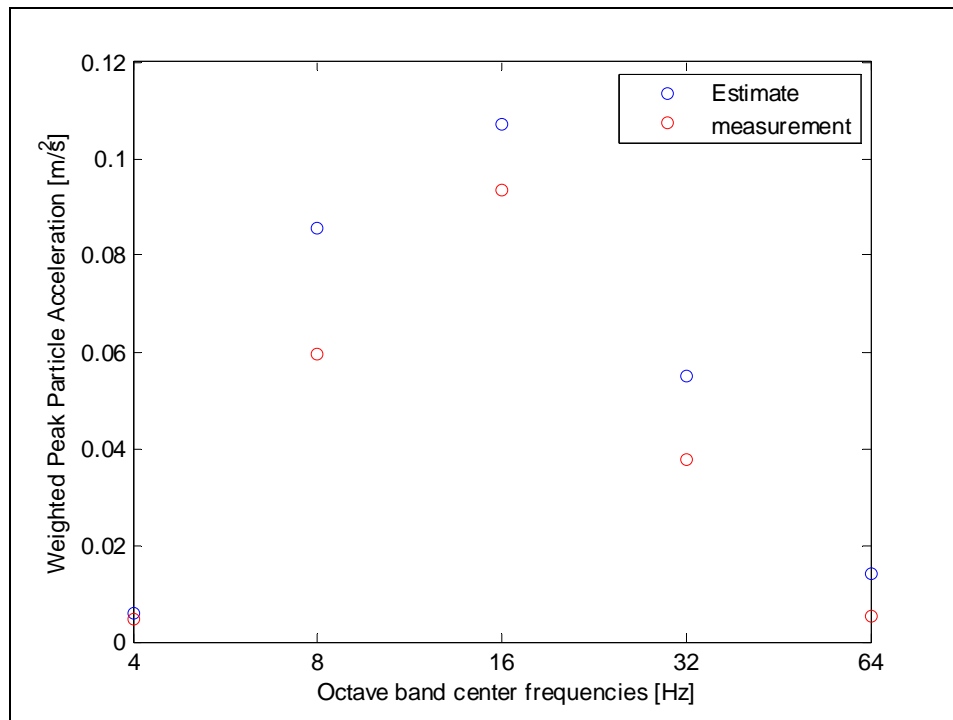
Figure 25 – Site A W_b Weighted Peak Particle Acceleration (z component) in Octave bands. Measured Internal exposure in W_b Weighted Peak Particle Acceleration (red dot). Estimated Internal exposure (blue dot)

For the prediction of the metrics in octave bands, the results for both sites are encouraging especially in the estimation of the weighted W_b Peak Particle Acceleration. For site A Figure 25 shows a slight overestimation in each band preserving the shape of the spectra, whereas for the site B (Figure 26) a better agreement between measurement and estimation has been found with the only exception of the 32 Hz band possibility due to the difference in the actual measurement position and the one used in the estimation of the building response.
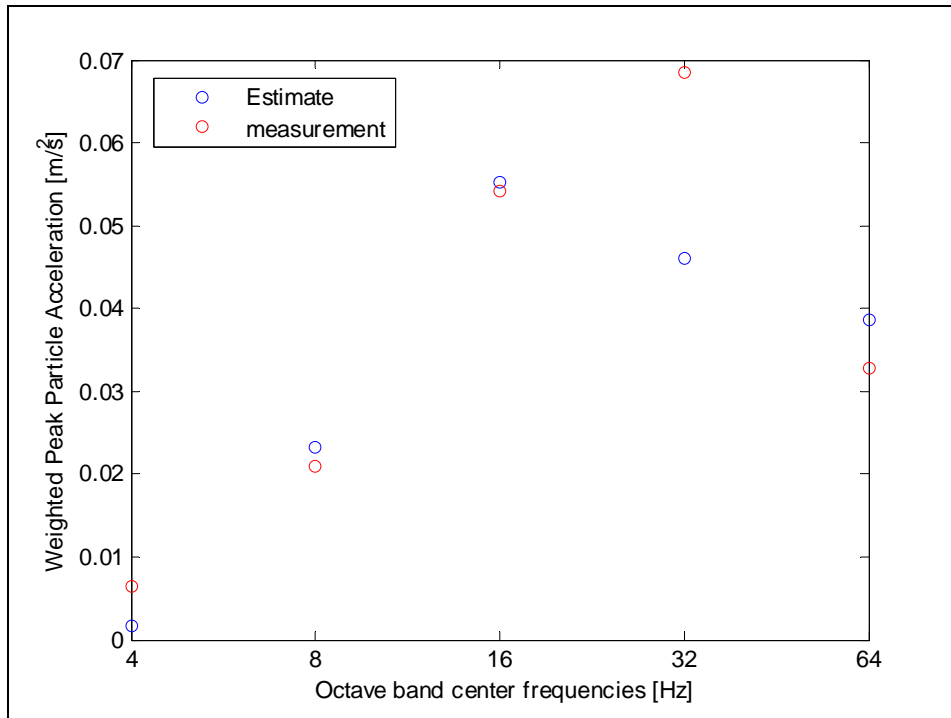
Figure 26 - Site B Weighted W_b Peak Particle Acceleration (z component) in Octave bands. Measured Internal exposure in W_b Weighted Peak Particle Acceleration (red dot). Estimated Internal exposure (blue dot)

Thus, Barkan's law has been shown to provide reasonable estimates of the external metrics from the control position vibration data with an uncertainty associated with the moving nature of the source (See section 6.3). In the case of internal exposure there is less opportunity to validate the results due to the difficulty in obtaining internal measurement positions. For this reason, there is greater confidence in the estimates of external vibration for the construction sites. This situation is the opposite of that for railways where the internal exposure estimates were based on a dense sampling of internal measurements.

The external and internal exposure estimated for the part of the construction yard where the measurement has been taken is assumed to be the same in the other parts of the residential environment exposed to construction activity.

4.4.1 PREDICTION CURVES
In this section we present the final form of the prediction curves used, in conjunction with the social survey data, to evaluate the exposure-response relationships reported in Technical Report 6. First we consider the question of the time period over which the exposure should be calculated.

A difficulty arises with construction vibration in considering the time period over which the exposure is to be evaluated. In the case of railway vibration this problem

does not occur because the exposure is effectively the same every day (except perhaps weekends), but for the construction sites every day's exposure was different (see Figure 12 and Figure 13). The question then arises as to whether a daily exposure adequately quantifies the overall exposure or whether the 'total exposure' accumulated over the entire length of the construction activities would be a more representative indicator of the potential annoyance. The latter would take account of length of construction programme and it could be argued that this more adequately represents the impact on the residential environment than a daily exposure which takes no account of the length of duration. For example one might expect greater annoyance from a site which continues working for a long period, perhaps years, than one where the work is completed within one day.

If using a daily exposure then a further question arises, since every day's exposure is different, as to which day should be evaluated. One option would be to select a worst case day. An alternative would be to use some measure of the average exposure for the period of construction activities, although in effect, such a measure would relate closely to a total exposure measure.

In the absence of definitive information, the exposure has been evaluated on a daily basis, calculated in a 10 hour time window, from 8 a.m. to 6 p.m., which are typical hours of work for construction during a weekday. In addition, the total exposure has been calculated, although essentially this produces the same data set multiplied by a factor since all residences in the study were assumed to be exposed for the same duration.

Considering the highest daily exposure, for Site A the maximum daily exposure by the piling operations was reached on the 21st day of long term monitoring as shown in Figure 12. In Figure 27 the decay of the external VDV (z component) with distance is presented. The exposure is evaluated from the long term monitoring (control) position at 6 meters from the site boundary (see section 4.2.1) and has been propagated according to Barkan's law incorporating the soil attenuation factors for the site obtained in section 4.3.2.

For site B, the maxiumum daily exposure caused by the pavement breaking/shallow excavation occurred on the third day of long term monitoring from Figure 13. The maximum daily exposure has been propagated from the control position data at 14 meters from the origin of the reference system as defined in section 4.2.1. The decay of the external VDV (z component) is also presented in Figure 27.

As the vibration exposure is a cumulative value the total vibration exposure has been calculated for both sites during the entire monitoring period. For Site A, a total VDV (z component) of 0.27 $m/s^{1.75}$ has been found over 62 days of monitoring whereas for site B a value of 0.19 $m/s^{1.75}$ over 37 days of monitoring. The value obtained has been propagated from the control position using Barkan's law as before. The results are shown for both sites in Figure 28.
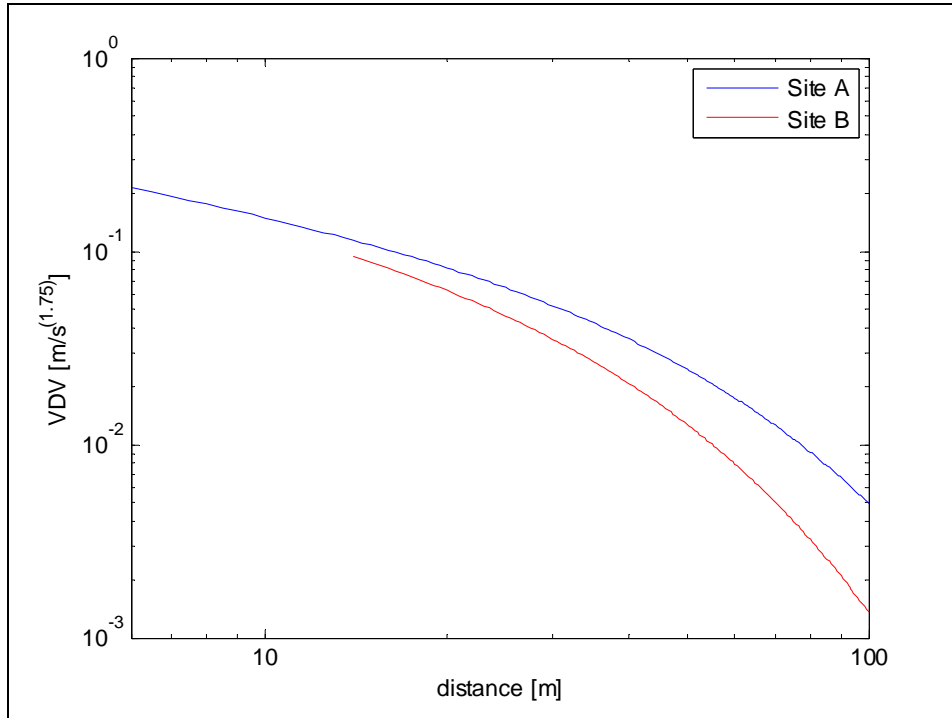
Figure 27 – VDV (z component) vs distance. External maximum daily exposure from CP with Barkan's Law. Site A (blue line) piling operation, Site B (red line) pavement breaking/shallow excavation. Daily exposure calculated over 10 hours. Graph in logarithmic scale
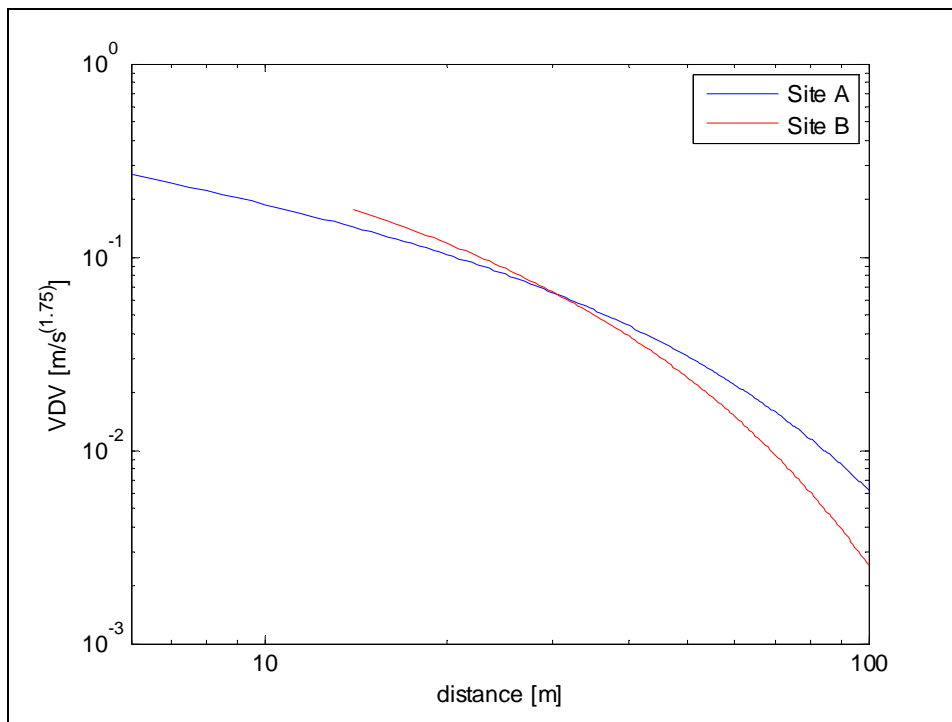
Figure 28 – VDV (z component) vs distance. Total external exposure propagated from CP with Barkan's Law. Site A (blue line) exposure calculated over 62 days. Site B (red line) exposure calculated over 37 days. Graph in logarithmic scale

5 VIBRATION EXPOSURE FROM INTERNAL ACTIVITY

5.1 VIBRATION CHARACTERISTIC

Internal sources have been defined as the set of vibration sources acting inside the residential property. Those are caused mainly by mechanical excitation such as washing machines or by human activity itself. Mechanical excitation may provide continuous vibration whereas human activity can be seen either as a continuous or a transitory source of vibration depending on the activity considered. In both the cases the vibration is propagated through the building across its structural elements such as columns, beams and floors and these interactions can be amplified or attenuated before being felt by the resident at the point of entry.

It is well known that each structural element has resonance frequencies that may amplify the transmission of energy when the excitation frequency is close to the resonant frequency. These resonance effects are more pronounced in structures with low damping. Light-weight and long span floors tend to have pronounced resonances with low damping which may potentially to cause annoying floor vibrations. The latter can be a problem in the design of some modern buildings where these structural elements are used.

In the literature, a recent case of annoying internal sources in the working environment can be found in the works of Sylvestre-Williams et al. (2010) where the rhythmic human activity from a gym placed at the top of an Toronto high rise building caused its oscillation at 2.3 *Hz* that could felt by the occupant eight floors below. In this study is also highlighted the importance of the transmission of the vibration through columns that has to be taken account in the design of buildings with more than fifteen floors.

Guidelines for the evaluation and estimation of building vibrations from human activity are provided in the works of Allen et al. (1987) and Allen (1990). Figure 29 shows the cases of vibration problems due to human activity, Figure 30 shows the minimum natural frequencies caused by human rhythmic activities for different type of construction, whereas in Figure 31 the suggested criteria for sinusoidal vibrations of short durations are shown from Allen et al. (1987).

Location	Date	Construction	Natural Frequency Hz	Measured Acceleration % g
DANCING				
1 Toronto	1970	Steel Joist	2.75	>10R
2 Winnipeg	1973	Steel Joist	5	5
3 Maryland	1974	Steel Joist	3	10R
4 Edmonton	1982	Steel Joist	5	4
ROCK CONCERTS				
5 Ottawa	1980	Precast Stands	2.4	34R
6 Edinburgh	1981	Wood on Steel	2.5	55R
AEROBICS				
7 Zurich	1977	Concrete	4.9	55R
8 Toronto	1983	Steel Joist	3.5	6R
9 Ottawa	1985	Concrete	4.4	0.4R
10 Ottawa	1986	Concrete	4.2	1R
WALKING (from Allen and Rainer 1976, Murray 1979))				
3 Floors		Steel Joist/Beam	4 to 4.5	
13 Floors		Steel Joist/Beam	5 to 7	
4 Floors		Steel Joist/Beam	7 to 9	

Note: R signifies resonance.

Figure 29 – Cases of vibration problems due to human activity (Allen et al 1987)

CONSTRUCTION	DANCE FLOORS, GYMNASIA	STADIA, ARENAS
Concrete (heavy)	7 Hz	5 Hz
Steel Joist (medium)	9 Hz	6 Hz
Wood (light)	12 Hz	8 Hz

Figure 30 – Minimum natural frequencies from rhythmic activity (Allen et al 1987)
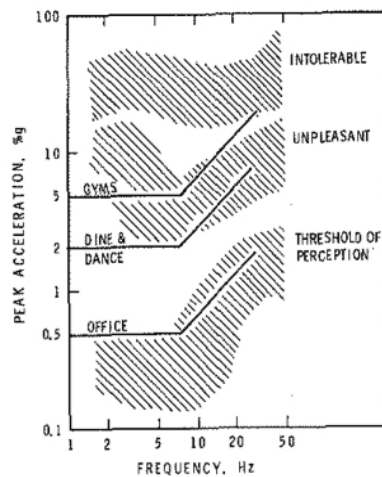
Figure 31 – Suggested criteria for sinusoidal vibration of short durations (Allen et al 1987)

NANR209 Technical report 3

5.2 METHODOLOGY

Figure 32 – Measurement Scheme for Internal Source

The possibility of perceptible vibration is determined by a combination of factors related to the strength and frequency of the source and the resonance frequency and damping of the structural elements involved in propagation. For the reasons given in the previous section, this problem is most likely in 'lively buildings' with long floor spans and low damping.

As highlighted in the final report it was not possible to access many flats in 'lively buildings' due to issues of privacy. However, measurements were performed where permission was made available including university accommodation, mainly tower blocks, housing students and families. Likewise the project was successful in performing internal source specific field trials at sheltered accommodation managed by local authorities.

The measurement approach (Figure 32) in this case relies on synchronized long term monitoring measurement in different parts of the building. Ideally the measurement should be conducted in empty apartments so as to ensure that the vibration recorded emanates from external dwellings. The estimation of the exposure is based on the calculation of the exposure during the long term monitoring period, that is 24 hours.

5.3 ANALYSIS

5.3.1 INTEGRITY CHECK
The time histories of the long term monitoring position have been checked in order to avoid the presence of contaminating sources.

5.3.2 EXPOSURE ESTIMATION
The exposure metrics have been calculated considering the z component of the acceleration time history for each long term measurement point for each property. The levels of exposure found are well below the minimum levels found for both railway and construction activity.

5.4 RESULT
The exposure metrics calculated over the 24 hour monitoring periods for each floor of each property type are reported in this section. Three property types are considered. The first is a sheltered accommodation denoted property type 01 (Table 11). The second and the third are university accommodation denoted property type 02 (Table 12) and 03 (Table 13).

Property Type 01	W RMS	W PPA	VDV	W RMQ
G. Floor	0.00017	0.032	0.016	0.00093
1st Floor	0.00029	0.015	0.013	0.00076

Table 11 – Property type 01 exposure metrics for internal sources (W stands for W_b weighting)

Property Type 02	W RMS	W PPA	VDV	W RMQ
G. Floor	0.00067	0.77	0.3	0.017
1st Floor	0.00052	0.09	0.056	0.032
2nd Floor	0.00057	0.09	0.057	0.033

Table 12 – Property type 02 exposure metrics for internal sources (W stands for W_b weighting)

Property Type 03	W RMS	W PPA	VDV	W RMQ
G. Floor	0.00057	0.62	0.25	0.014
1st Floor	0.012	6.1	2.97	0.17
2nd Floor	0.00039	0.044	0.032	0.019

Table 13 - Property type 03 exposure metrics for internal sources (W stands for W_b weighting)

The exposure for the 1st floor of property type 03 has not been used in the derivation of the exposure response relationship for internal vibration because the exposure calculated was strongly contaminated by local activity.

6 UNCERTAINTIES

6.1 METHODOLOGY

6.1.1 MEASUREMENT UNCERTAINTIES

Any measured quantity has an associated margin of doubt. In the case of vibration levels measured in the residential environment, this uncertainty can usually be attributed to factors influencing the measurement "chain" rather than the measuring instrumentation. This is not normally the case with laboratory-based measurements, for which a number of evaluation procedures to determine uncertainties have been established.

Before any uncertainty evaluation can be done it is necessary to decide how the measurement result is to be used. If it is for short-term comparisons, say between events on a particular day, there is unlikely to be any significant change in long-term variables like the weather. If however the measurements are for long-term use, to be compared with data taken at some time in the future, then the long-term uncertainty magnitudes should be considered.

Some variables affecting the measured levels can often not be controlled. In this case it will be necessary to take a view as to whether measurements should be repeated and if so, how often, to obtain the desired confidence in the results. In general, an estimate of the uncertainty in a measured value gives an idea of the quality of the measurement, but in reality the quality of a measurement can only be determined in the context of the purpose for which the measurement was made.

It is necessary to quantify the uncertainties in an acceptable and uniform manner. To achieve this, two quantities may be specified:

1. The "confidence interval", which is the margin within which the true value being measured can be said to lie, and
2. The "level of confidence", which is a number expressing the degree of confidence in the result.

To obtain these quantities, it is necessary to carry out a procedure that considers each separate contribution to the uncertainty chain, evaluates its contribution, and then combines them according to set statistical procedures. The usual approach adopted is to set up an "uncertainty budget", often found in the form of a spreadsheet, in which the various sources of uncertainty, the pertinent magnitudes, the statistical processes and the final combined results can all be conveniently listed.

In many instances, including vibration measurements, the sources and values of uncertainties may not be known or cannot be readily evaluated. In such cases

reasonable estimates based on experience can be made and the importance, or otherwise, of the decision evaluated alongside other known variables. Alternatively, an overall statement of uncertainty can be derived from statistical maxima based upon sets of practical measurements, which encompass the likely statistical variations.

6.1.2 *FORMULATION OF UNCERTAINTY BUDGET*

For our uncertainty sources the "confidence interval" is defined as the half width of the uncertainty magnitude, i.e. if the magnitude is *a,* the "confidence interval" *x* will be *a/2*, expressed as:

$$x = \pm \frac{a}{2} \tag{1.10}$$

The standard uncertainty associated with the "confidence interval" has to be expressed at the 68% "level of confidence" (Bell 2001), which corresponds to one standard deviation each side of the mean. The data for defining our "confidence interval" are taken from literature or from previous analysis, therefore we assume that the real value can fall anywhere in the "confidence interval" with equal probability (rectangular distribution). For this distribution the standard uncertainty is:

$$u = \frac{x}{\sqrt{3}} \tag{1.10}$$

Having obtained those quantities for each source of uncertainty, which consider each separate contribution to the uncertainty chain, we need to combine them according to set statistical procedures by setting up an "uncertainty budget", in which each source of uncertainty is located in the relevant area. The zones considered are:

- Source
- Path
- Receiver

The following procedure is based on Bell (2001). It is accepted that this procedure may be overcomplicated for certain situations, especially where one or two uncertainties dominate all others. It is important however that when uncertainty magnitudes are quoted; they are in the same units and refer to the same level of confidence – 68%. This procedure is not prescriptive. If the nature of the situation is such that there is little relevant information available to make an estimate of a particular uncertainty, then a reasoned guess should be made and evaluated alongside other known quantities. It is also considered reasonable to ignore some small or

irrelevant uncertainties in the final assessment. When drawing up the full uncertainty budget, the user can incorporate the following steps into a single spreadsheet, or use individual spreadsheets, or simply notes showing the way in which the decisions have been reached. A flow chart summarizing this process is presented in Table 14.
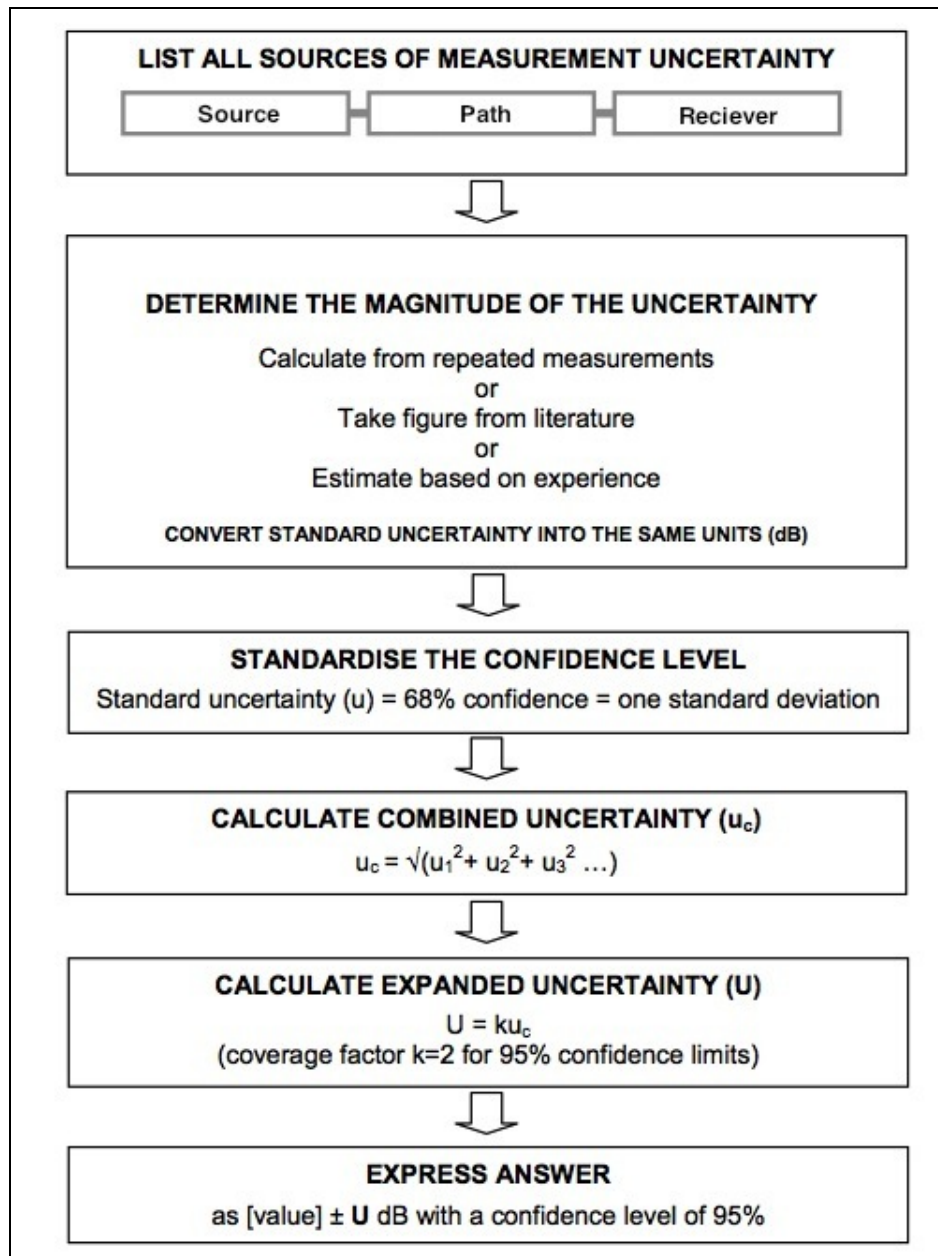

Table 14 – Flow chart representing the process for the calculation of the uncertainty of the measurement (Craven & Kerry 2001).

In the following sections the methodology described above has been applied for the vibration sources considered in the study.

6.2 UNCERTAINTY IN EXPOSURE FROM RAILWAYS

The measurement of the exposure from railways relies on the methodology explained in 3.2 and 3.3.3. The uncertainty for a given case study depends on the type of measurements taken on site. The following categories can be identified:

1. Internal Measurement.
2. External Measurement.
3. No Measurement.

Each of these cases will be influenced by different sources of uncertainty linked with the lack of information for the determination of the exposure. Of course, the further we go from the property, the more sources we have to take in account and the less precise our measurement or estimation of the exposure will be. In this section we are going to describe the main source of uncertainty for each of the measurement types listed above.

6.2.1 INTERNAL MEASUREMENT

When an internal measurement is allowed, the vibration inside the property is measured, if possible in the room where the respondent says that they are worst affected. Where possible, the accelerometers are positioned in the centre of the floor span as suggested by BS ISO 14837-1:2005 (BSI 2005). The internal measurement is performed in the absence of the occupants in order to record only the vibration of the floor unloaded by the mass of a person; therefore, under ideal conditions an internal measurement represents the worst case in the determination of the human exposure as suggested by the BS 6472-1:2008. The exposure as defined in BS 6472 differs from the true exposure in that for practical reasons (a) the floor is not generally loaded by a person during the measurement and (b) whilst vibration will often be perceived when sitting on a chair, lying on a bed etc and the effect of furniture on the transmission is not generally taken into account. In this study the objective is to estimate as closely as possible the exposure as defined in the standard rather than the true exposure and therefore, uncertainty associated with floor loading and furniture is not included. The uncertainties to be evaluated are those related to the difference between our estimated vibration exposure and that which would be obtained at the worst case 'point of entry' location. Therefore, an uncertainty associated with measurement position arises because the centre of the room is not always available for measurement.

An estimation of the dynamic range of this source of uncertainty can be made from H. Xia et al. (2009) who did experimental measurements of building vibrations induced by railway traffic. Measuring the level of vibration in the corner and in the centre of the room, they found that the level of vibration inside a room of a multi-story building at 14 *m* from the railway line depended on the speed of train and the train type. In detail, the level of vibration between the two measurement points is the same for freight and fast trains (up to 100 *km/h*) whereas for passenger trains a variation of almost 4 *dB* in the level of vibration is noted between the two points.

Therefore, we use this experimental observation as the dynamic range of the uncertainty source defined above because it can also represent a sort of worst-case scenario encountered in our fieldwork in terms of train speed, train type and distance from the railway line.

Other sources of uncertainty related to the internal measurement are the mounting of the instrument on soft covering like carpet or linoleum (See Technical Report 1). From Table 5 in the Technical Report 1 the maximum uncertainty related to the mounting condition has a magnitude of 3 *dB* and the associated uncertainty is ±1.5. The uncertainty due to the calibration of the instrument is negligible (see Technical Report 1) and the uncertainty related to the data processing is quantified as ±1.4 (Craven & Kerry 2001). All these sources are considered negligible in the total evaluation of the uncertainty due to the exposure from internal measurement because the standard uncertainty associated is less than 1 *dB* according to (1.12).

Another source that we consider negligible is the variation of the daily traffic on the railway line, because it is a long term variable and at this stage we are only working to the time interval defined by the 24 hour measurement at the control position.

6.2.2 EXTERNAL MEASUREMENT

The case becomes less ideal when we consider an external measurement. Here, we only have information about the level of vibration outside the property and we miss the information related to the vibration inside the property. Therefore, we need to estimate the velocity ratio between the measurement point and the point of entry where the greatest adverse comment can be predicted. This situation can be identified inside our database as an internal measurement taken at the first floor of the property. The estimation of the exposure at the first floor of the property can be done through the velocity ratio between the ground outside the property and the foundation for estimating the coupling plus the velocity ratio between the foundation and a point on the upper floor in the building. The estimation of the order of magnitude of the velocity ratio for the coupling and the floor response can be done using values from the Nordtest method (Nordtest 1991), In this way we will build the dynamic range associated with the missing of information related to the building response. If we consider buildings without basement (frame-type foundation) the coupling will be -2 *dB* whereas the upper floor amplification of a two-storey house with timber floor is almost 20 *dB*. If we add the values, the level difference between a point in the ground and a point in the building is 18 *dB*. Of course, this value is based on a simple estimation taking into account light structures that are more affected by ground-borne vibration generated by trains.

Another source of uncertainty that we have to take in account is that due to the velocity ratio's dependence on the source, the complex mechanisms that generates the vibrations and the possibility of the near field effects due to the distance between

control position and the property. We estimate that this uncertainty has a range of 8 *dB* based on the results of measured velocity ratios.

6.2.3 No Measurement

The worst scenario is when no measurements are taken for determining the exposure of the respondent that took part in the social survey. In this case the information available are the measured 24 hour vibration time histories from the control position and the internal measurement data made in properties of similar type at a similar distance from the same railway track. As explained in 3.3.3.3 the hypothesis of similarity has been used for estimating the internal exposure where the exposure measurement has not been taken. This is justified by the high success rate of internal measurement, around 56%, that has permitted a good "sampling" of the internal vibration activity in all the measurement sites.

The uncertainty related to the estimation of the exposure includes those sources of uncertainty already listed above when an internal measurement is taken plus the uncertainty due to propagation from the control position to the property. Of course this kind of uncertainty is difficult to estimate because it is related to propagation phenomena that could be affected by local effects due the soil profile. Unfortunately, the geological conditions that promote efficient propagation have not been well documented and are not fully understood. Shallow bedrock or stiff clay soil are often involved. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. From the literature (FTA 2006) this effect can cause a maximum amplification of 10 *dB* in the value of the ground acceleration and so our initial estimate of the dynamic range for this source is 10 *dB*.

6.2.4 Results

The uncertainty budget for evaluating the human exposure to vibration in residential environment caused by railway activity is presented in Table 15.

Source of Uncertainty	Magnitude	Confidence Interval	Standard Uncertainty
Source			
Variance in Velocity Ratio	8 *dB*	±4 *dB*	±2.3 *dB*
Path			
Ground Condition	10 *dB*	±5 *dB*	±2.9 *dB*
Receiver			
Building Response	18 *dB*	±9 *dB*	±5.2 *dB*
Measurement Position	4 *dB*	±2 *dB*	±1.1 *dB*

Table 15 **- Uncertainty budget for human exposure by railway activity**

NANR209 Technical report 3

For each measurement type, an uncertainty budget has been created that takes into account the relevant sources of uncertainty. The specific uncertainty budget for the measurement type internal, external and no measurement are shown in Table 16, Table 17 and Table 18.

Source of Uncertainty	Magnitude	Confidence Interval	Standard Uncertainty
Receiver			
Measurement Position	4 *dB*	±2 *dB*	±1.1 *dB*

Table 16 – Uncertainty budget for internal measurement

Source of Uncertainty	Magnitude	Confidence Interval	Standard Uncertainty
Source			
Variance in Velocity Ratio	8 *dB*	±4 *dB*	±2.3 *dB*
Receiver			
Building Response	18 *dB*	±9 *dB*	±5.2 *dB*

Table 17 – Uncertainty budget for external measurement

Source of Uncertainty	Magnitude	Confidence Interval	Standard Uncertainty
Path			
Ground Condition	10 *dB*	±5 *dB*	±2.9 *dB*
Receiver			
Measurement Position	4 *dB*	±2 *dB*	±1.1 *dB*

Table 18 – Uncertainty budget for 'no measurement' cases

For each measurement type we have to combine the appropriate sources of uncertainty. The combined uncertainty can be obtained by Table 14 in the following way:

NANR209 Technical report 3

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + K} \qquad (1.11)$$

Where u_1, u_2, u_3 are the standard uncertainties for each measurement type. The method summarized in Table 14 expresses the final uncertainty U with a confidence interval of 95 % which means taking twice the combined uncertainty calculated in (1.11).

$$U = 2 * u_c \qquad (1.12)$$

The final uncertainties for measurement types considered for deriving the exposure response relationship for railway activity (see section 3.3.3) are shown in Table 19.

Measurement Type	Final Uncertainty
Internal Measurement	±2.2 dB
No Measurement	±6.2 dB

Table 19 - Final Uncertainty from railway activity per measurement types

When no internal measurement has been made it is more reliable to estimate exposure from an internal measurement in a comparable property than from an external measurement. Therefore, cases of 'external measurement' have been treated the same as 'no measurement' cases and only the latter is considered in Table 19.

6.3 UNCERTAINTY IN EXPOSURE FROM CONSTRUCTION

The methodology related to the exposure estimation from construction can be found in section 4.

The estimation of the exposure from construction relies on the propagation of the exposure metrics from the long term monitoring (control) position across the residential environment using the semi-empirical relationship:

$$M(d) = M_0 \sqrt{\frac{d_0}{d}} e^{-\alpha(d-d_0)} \qquad (1.13)$$

where M is the metric at distance d from the origin of the system and M_0 is the metric evaluated at the control position at distance d_0 from the origin of the system.

α is the material attenuation obtained by fitting the experimental data from the controlled experiments as described in section 4.3.2 under the assumption that Rayleigh waves predominate.

As highlighted in section 4.4, the control position is a good predictor of the external vibration in the worst case scenario where the source is close to the control position as shown in Figure 23 but an uncertainty estimate needs to consider the moving nature of the source.

This uncertainty can be evaluated considering the variation of the vibration level expressed in weighted peak acceleration between the control position and the closest external accelerometer of the array (see section 4.2).

For site A, we have considered just the contribution from piles P1 and P2 because exposure from other piles was affected by shielding (see Figure 14). The same data will be used to estimate other uncertainties for site A. Using this data, the uncertainty related to the moving nature of the source is estimated to have a range of 8 *dB*. For site B, considering two decays during the controlled experiments with the moving source approaching the control position, the uncertainty is estimated at 8 *dB*.

As found in the section 4.3.2 an uncertainty needs to be declared for taking into account the daily variation of the vibration far from the source due to ground condition. This uncertainty has been estimated considering the variation of the external vibration level from the accelerometers of the array that are at a distance greater than 30 *m* from the moving source.

For the site A we have considered the average variation of the last two elements of the array obtaining 4 *dB* as the dynamic range of uncertainty whereas, for site B, 13 *dB* has been obtained.

An uncertainty related to the building response is obtained evaluating the variation of the amplification factor defined as in the section 4.3.4 from the moving source. As in the case of railways, the building response is evaluated in the worst case scenario that consists of an internal measurement on the first floor. The latter can be found in the set of measurements carried out at site A.

The magnitude of the uncertainty is 5.5 *dB*.

As explained in section 4.3.1 the propagation may be affected by the shielding caused by the cellars of the houses. An estimation of the shielding can be found using the empirical relation from Richart et al. (1970) that a trench can reduce surface vibration propagation significantly at frequencies for which the ratio of the depth of the trench to the Rayleigh wavelength is greater than about 0.6.

$$\frac{d}{\lambda_R} > 0.6 \qquad (1.14)$$

where d is the length of the trench and λ_R is the wavelength of the incoming Rayleigh wave. According to Beskos et al. this empirical relation can provide a vibration reduction of 12 *dB* (Garcia-Bennett et al. 2010). For a trench, the reduction of the vibration is only acting along its depth but for the cellar of the house we need also to take into account the width and the length. Therefore, we need to apply the relation (1.14) along each dimension of the cellar. In this way an estimation of the frequencies reduced by the cellar can be made with the assumption that the Rayleigh wave speed is 240 *m/s*. If the cellar has a length of 12 *m*, a width of 8 *m* and depth of 3 *m* it will attenuate all the frequencies above 12 *Hz*. The latter is in the range of the frequencies generated by the piling activity demonstrating that the cellar of the house can act as a vibration barrier and attenuate the level of vibration. Therefore, the 12 *dB* reduction will be assumed to be the uncertainty magnitude related to shielding.

6.3.1 *RESULTS*

The formulation of an budget for the evaluation of the uncertainty from the prediction method is obtained averaging the uncertainty obtained in both the measurement sites. The results are shown in Table 20.

Source of Uncertainty	Magnitude	Confidence Interval	Standard Uncertainty
Source			
Control Position	8 *dB*	±4 *dB*	±2.3 *dB*
Path			
Daily Variation	8.5 *dB*	±4.25 *dB*	±2.4 *dB*
Shielding	12 *dB*	±6 *dB*	±3.5 *dB*
Receiver			
Building Response	5.5 *dB*	±2.75 *dB*	±1.6 *dB*
Measurement Position	4 *dB*	±2 *dB*	±1.1 *dB*

Table 20 – Uncertainty budget for the estimation of the exposure from construction

The final uncertainty related to the external estimation of the exposure is obtained by combining the source and path uncertainties using (1.11) and (1.12). The final

uncertainty for the estimation of the internal exposure is obtained by combining that of the external estimation with those related to the receiver, i.e. the building response and the measurement position which were evaluated in the same way as for the railway case. Results are shown in Table 21.

As in the railway case the uncertainty related to the instrument calibration, the mounting condition and the data processing are considered negligible.

Measurement Type	Final Uncertainty
External measurement	±9.6 *dB*
Internal measurement	±10.4 *dB*

Table 21 - Final uncertainty exposure from construction activity.

6.4   UNCERTAINTY IN EXPOSURE FROM INTERNAL SOURCES

The methodology for the estimation of the exposure from the internal sources is explained in section 5.2.

As explained in section 6.2.1 an internal measurement represents the worst case scenario in the determination of the exposure and therefore the best way for measuring this value. The only source of uncertainty related to this measurement is the one linked to the instrument position evaluated with a magnitude of 4 *dB* as in the railway case.

6.4.1   RESULTS

The final uncertainty related to the exposure from internal sources is quantified in ± 2.2 *dB*.

NANR209 Technical report 3

7 CONCLUSION

This report has presented the different methodologies used for calculating the human exposure to vibration in residential environments. It complements Technical Report 2 in which the measurement of human response is described. Vibrations from railways, construction and internal domestic activity have been studied in order to provide data with a variety of vibration characteristics. Each of these sources has required a distinct strategy for measuring and calculating the exposure.

7.1 RAILWAY

In the case of railway vibration, the quasi-permanent nature of the source means that it is logistically possible to obtain internal measurements in a large number of cases in synchronisation with the social survey. A key feature of the methodology is the use of a long term monitoring position, or control position, placed within the residential environment which acquires a measure of the vibration time history for a minimum of 24 hours. Synchronised, internal measurements were made inside as many properties as possible (about 56% of the total) so as to capture at least a few train passes in each case (generally more than six). The average (frequency dependent) velocity ratio between the internal and the control measurements was then used to filter the entire time history recorded at the control position so as to obtain an estimate of the 24 hours exposure inside the property. In this way any exposure metrics can be estimated.

In cases where no internal measurement was possible, the internal exposure has been estimated based on the value obtained from measurement inside a nearby property of similar type and at similar distance to the railway. In view of the high success rate for obtaining internal measurements these estimates are thought to be more reliable than those obtained from external measurements outside the property.

7.2 CONSTRUCTION ACTIVITY

Construction activity is the product of different operations involved in a construction process. The latter has both a transitory and an external impact on the living environment and can produce vibration of varying character, including continuous and transient. In order to produce a sample of sufficient size it was necessary to consider large scale construction operations, both in terms of dimension and duration of the works. The survey has been conducted using light railway construction works which has the advantage that essentially the same operations are repeated along the length of the track, thereby causing similar vibration exposure in a variety of residential areas. However, unlike the railway case, it is not logistically possible to obtain more than a small number of internal measurements without adversely affecting the social survey. Therefore, the exposure estimation relies more on prediction which is based on semi empirical relationships well known in the construction sector.

As with railways, a long term monitoring (control) position is employed at the boundary between the construction site and the living environment. Monitoring takes place during the operations which, in consultation with the construction manager, are considered likely to be felt by the residents. The control position is used to record the entire life cycle of the construction operations which required 63 and 36 days respectively on two different sites. More intensive measurements, consisting of an internal position and an external array, have also been conducted alongside the long term monitoring during the days of major activity. These measurements are then used to estimate the properties of the ground involved in the propagation of the vibration across the residential environment by curve-fitting the well-established semi-empirical relationship, Barkan's law.

Having characterised the ground in this way the exposure recorded at the control position can then be 'propagated' through the residential environment by calculation. The internal exposure is obtained using a velocity ratio to correct for the attenuation from the ground to the internal positions.

The exposure is evaluated both as a 'daily exposure' for the day of maximum exposure and as a 'total exposuree' for the entire monitoring period. The difficulty of obtaining internal measurements means that a full independent validation of the internal exposure estimates is not possible. However, Barkan's law is considered to provide reliable propagation of the external exposure.

7.3 INTERNAL SOURCES

Internal sources are indentified as the mechanical and human excitation created inside the property. They can be transitory or static depending on the nature of the excitation. In this case the estimation of the exposure is based on long term internal measurement in each floor of the building. The measured level of the exposure was generally low in comparison with that from the other sources considered.

It is common thinking that annoyance from internal sources is most evident in 'lively' buildings, however, residential buildings of this type were not accessible for the survey which possibly explains the low exposure levels obtained.

7.4 UNCERTAINTY

It was considered essential to estimate the uncertainties involved in the measurement and prediction of vibration exposure. The uncertainty evaluation is based on the well-established methodology for the evaluation of the uncertainties in environmental noise measurement (Craven & Kerry 2001) which involves the drawing up of an uncertainty budget. The various sources of uncertainty have been identified and their magnitudes estimated from literature or from experimental data.

For railway activity the uncertainty has been evaluated as ±2.2 *dB* in cases where internal measurement was possible and ±6.2 *dB* where it was not.

NANR209 Technical report 3

For construction activity the uncertainty analysis is based on the semi empirical relationship used for the exposure assessment through the residential environment. The estimated uncertainty is ±9.6 *dB* for estimates of the external exposure and ±*10.4 dB* for internal exposure. The most important factor is the moving nature of the construction source because it has been proved that the methodology works in the worst case scenario where the source is close to the residential environment represented by the long term monitoring position.

For internal vibration sources the uncertainty, being based on long-term internal measurements, is relatively small, ±2.2 *dB*

8 REFERENCES

Allen, D.E., 1990. Building vibrations from human activities. *Concrete International: Design and Construction*, 12(6), pp. 66-73.

Allen, D.E., Rainer, J.H. & Pernica, G., 1987. Building vibration due to human activities. In *Building Structures*, 17(20), pp. 438-447.

ANSI, 2001. *American National Standard to the Evaluation of Human Exposure to Vibration in Buildings*.

Athanasopouls, G.A. & Pelekis, P.C., 2000. Ground vibrations from sheetpile driving in urban environment: measurements, analysis and effects on buildings and occupants. *Soil Dynamics and Earthquake Engineering,* 19(5), pp. 371-387.

Banverket, 2002. *DNR.S02-4235/SA60 Buller och Vibratonier, Fran Sparburen Linjeetrafik,*

Barkan, D.D., 1960. *Dynamics of Bases and Foundations*, McGraw-Hill Book Co.

Bell, S.A., 2001. *A Beginner's Guide to Uncertainty of Measurement. Measurement Good Practice Guide No 11*.

BSI, 2009. *BS 5228-2:2009 Code of practice for noise and vibration control on construction and open sites*.

BSI, 2008. *BS 6472-1: Guide to evaluation of human response to vibration in buildings (1 Hz to 80 Hz) – Part 1: Vibration sources other than blasting*.

BSI, 2005. *BS ISO 14837-1:2005 Mechanical vibration. Ground-borne noise and vibration arising from rail systems. General guidance*.

Clough, W. & Chameau, J.-L., 1980. Measured effects of vibratory sheetpile driving. *Journal of the Geotechnical Engineering Division,* 106(10), pp. 1081-1099.

Craven, N.J. & Kerry, G., 2001. *A good practice guide on the sources and magnitude of uncertainty arising in the practical measurement of environmental noise*.

Dawn, T. & Stanworth, C., 1979. Ground vibrations from passing trains. *Journal of Sound and Vibration*, 66(3), pp.355-362.

Dowding, C., 1996. Construction vibrations, Prentice-Hall.

FTA, 2006. *Transit Noise and Vibration Impact Assessment*. Available at: www.fta.dot.gov/documents/FTA_Noise_and_Vibration_manual.pdf [Accessed March 30, 2011]

Garcia-Bennett, A., Jones, C.J.C. & Thomposon, D.J., 2010. A numerical investigation of railway ground mitigation using a trench in a layered soil. In *10th International Workshop on Railway Noise*, pp.315-322.

Griffin, M.J., 1996. *Handbook of human vibration*, Elsevier.

Gutowski, T.G. & Dym, C.L., 1976. Propagation of ground vibration: a review. *Journal of Sound and Vibration*, 49(2), pp.179-193.

Institute for German Standardization, 1999. *Vibration in Buildings - Effects on Person in Building*.

ISO, 2003. *ISO 2631-2 (2003): "Part 2: Continuos and Shock-induced vibrations in buildings (1Hz to 80 Hz).*

Klaeboe, R. & Öhrström, E., 2003. Vibration in dwellings from road and rail traffic-- Part III: towards a common methodology for socio-vibrational surveys. *Applied Acoustics*, 64(1), pp.111-120.

Klæboe, R. & Turunen-Rise, I., 2003. Vibration in dwellings from road and rail traffic--Part II: exposure-effect relationships based on ordinal logit and logistic regression models. *Applied Acoustics*, 64(1), pp.89-109.

Krylov, V., 1996. Vibrational impact of high speed trains. I. Effect of track dynamics. *The Journal of the Acoustical Society of America*, 100(5), pp. 3121-3134.

Lombaert, G. & Degrande, G., 2009. Ground-borne vibration due to static and dynamic axle loads of InterCity and high-speed trains. *Journal of Sound and Vibration*, 319(3-5), pp.1036-1066.

Madshus, C., Bessason, B. & Harvik, L., 1996. Prediction model for low frequency vibration from high speed railways on soft ground. *Journal of Sound and Vibration*, 193(1), pp.195-203.

Nelson, P., 1987. Transportation noise reference book, Butterworths.

Nordtest, 1991. *NT-ACOU 082: Buildings: Vibration and shock, evaluation of annoyance.*

Norwegian Council for Building Standardization, 1999. *NS 8176: Vibration and shock - measurement of vibration in buildings from land based transport and guidance to evaluation of its effects on human being*.

Ogren, M. & Ohstrom, E., 2009. Effects of railway noise and vibrations on sleep - experimental stuides within the Swedish research program TVANE. In *Euronoise 2009*.

Ohstrom, E., Ogren, M. & Jerson, T., 2009. Effects of railway noise and vibration in combination: field and laboratory study. In *Euronoise 2009*.

Ostendorf, C., 2002. Nine Years of Dutch Experience in the Evaluation of Vibrations in Relation to Nuisance. *Low Frequency Noise, Vibration and Active Control*, 21(4), pp.219-228.

Rathe, E., 1969. Note on two common problems of sound propagation. *Journal of Sound and Vibration*, 10(3), pp.472-479.

Richart, F., Hall, J. & Woods, R., 1970. *Vibrations of soils and foundations*, Prentice-Hall Inc.

Rix, G.J., Lai, C.G. & Wesley Spang, A., 2000. In Situ Measurement of Damping Ratio Using Surface Waves. *Journal of Geotechnical and Geoenvironmental Engineering*, 126(5), pp.472-480.

Sheng, X., Jones, C.J.C. & Thompson, D.J., 2003. A comparison of a theoretical model for quasi-statically and dynamically induced environmental vibration from trains with measurements. *Journal of Sound and Vibration*, 267(3), pp.621-635.

Svinkin, M., 1999. Prediction and Calculation of Construction Vibrations. In *24th Annual Members Conference Deep Foundation Institute.* Available at: www.vulcanhammer.net/svinkin/prediction.php [Accessed March 30, 2011]

Svinkin, M., 2002. Predicting soil and structure vibrations from impact machines. *Journal of Geotechnical and Geoenvironmental Engineering,* 128(7), pp.602-612.

Sylvestre-Williams, N., Rimrott, B. & Cho, J., 2010. The vibration of a high rise building's columns due to rhythmic activity. In *Internoise 2010*.

Turunen-Rise, I., Brekke, A. & Hårvik, L., 2003. Vibration in dwellings from road and rail traffic--Part I: a new Norwegian measurement standard and classification system. *Applied Acoustics*, 64(1), pp.71-87.

Wiss, J., 1981. Construction vibrations: state-of-the-art. *Journal of the Geotechnical Engineering Division*, 107(2), pp.167-181.

Wiss, J. & Parmele, R.A., 1974. Human perception of transient vibrations. *Journal of the Structural Division*, 100(4), pp.773-787.

Woodcock, J., Peris,E., Sica,G., Moorhouse,A., & Waddington,D. 2009. Investigations to measure human exposure to vibration in residential environments. In *Euronoise 2009*.

Woods, R.D. & Jadele, L.P., 1985. Energy Attenuation Relationships for Construction Vibrations. In *Vibrations Problems in Geotechnical Engineering*. pp. 229-246.

Woods, R., 1997. *Synthesis of Highway Practice 253 Dynamic effects of pile installations on adjacent structures*, National Academy Press.

Xia, H., Zhang, N. & Cao, Y.M., 2005. Experimental study of train-induced vibrations of environments and buildings. *Journal of Sound and Vibration*, 280(3-5), pp.1017-1029.

Xia, H., Chen,J., Wei,P., Xia,C., De Roeck,G., & Degrande,G. , 2009. Experimental investigation of railway train-induced vibrations of surrounding ground and a nearby multi-story building. *Earthquake Engineering and Engineering Vibration*, 8(1), pp.137-148.

Zapfe, J., Saurenman, H. & Fidell, S., 2009. *TCRP Web-Only Document 48: Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit*.