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On the assessment of the human exposure from vibration caused by railway construction

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When constructing large infrastructure, such as railways, close to living environments it is important to know how residents respond to construction vibration. In this framework, the University of Salford, within the project "Human response to vibration in residential environments", has provided, for the first time, an exposure-response relationship for vibration caused by railway construction in the living environment based on 350 case studies. The evaluation of the response was conducted with a face to face questionnaire whereas the exposure was measured through vibration measurement. This paper deals with the exposure side of the problem describing the novel approach developed for the assessment of human exposure. Considering the construction processes as a linear sequence of operations that move along a predefined route as the work progresses, the methodology relies on combined long term and array measurements for evaluating the exposure propagation through the residential environment based on semi empirical relationship well known in the construction field. Results are presented for two construction processes. [Work funded by the Department for Environment, Food and Rural Affairs (Defra) UK]

INTRODUCTION

The needs of a better connected society have brought the design of traffic system closer to urban areas. In the U.K., the most recent example of this approach can be found in light and urban rail systems such as the Metrolink in Manchester and the Crossrail in London.

Building these large infrastructures involves complex construction operations that, sometimes, are performed during the whole day, generating a large amount of vibrations. For this reason, construction vibrations are generally considered more in terms of building damage and soil settlement[1], especially when high energy operations like piling or compaction are involved, but with the scenarios depicted above, attention needs to be addressed to the assessment of the human response in buildings too. In this sense, projects like Crossrail[2] and Edinburgh tram adopt limits which lie within the national standard for the evaluation of the human response in buildings, BS 6472-1:2008[3]. On the other hand, in the U.K. construction standard BS 5228-2:2009[4] an attempt has been made to relate the human response to the construction vibration using PPV (Peak Particle Velocity) as a descriptor for the exposure since this parameter is likely to be more routinely measured based upon the more usual concerns over potential building damage[4]. A possible criticism of these regulations can be oriented towards their limits which may have a laboratory origin[5], and not so realistic for describing the human response in the

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living environment. An alternative “tool” for exploring the human response in residential environments is to build an exposure response relationship, which describes the response of a percentage of the population, express in annoyance, as a function of the level of vibration to which they are exposed.

A few studies have been done for vibration from transportation sources, like road and rail traffic, because their quasi permanent nature, which means that the vibration generated is repeatable and predictable, facilitates the study design. These studies are suitable for describing a “steady state” problem where the vibration source is already present in the living environment. Instead, construction has a disruptive effect on the environment and it can be classified as “non-steady state” problem. In this category falls, for example, another problem: the increase of rail traffic on existing rail lines.

The consequences of operating in this scenario should be considered by European projects like Cargovibes[6] in light of the future increase of the European freight traffic.[7] In fact, the difference between the “steady” and “non-steady” problem may be found not only in the evaluation of the exposure but in the potential affect on the annoyance from vibration as well.

A first step in the exploration of the community response to vibration for a “non-steady state” problem has been carried out at the University of Salford deriving an exposure response relationship for railway construction. In the following sections the method for assessing human exposure will be presented.

FORMULATION OF THE PROBLEM

Vibration activity from construction consists of different sources depending on the operations involved on the construction site. According to Wiss[8] the vibration types from construction cover the entire range of vibration affecting the residential environment. In fact construction vibration can be classified as: transitory or impact, steady state or continuous and pseudo-steady or random. In the framework of the project “Human response to vibration in residential environments”, construction activity is considered as a transitory source acting externally to the residential environment[9].

The transitory nature of the source creates logistical difficulties in obtaining an adequate sample size. Therefore, for assessing exposure and annoyance due to construction vibration it is important to consider the size of the construction site and the duration of the work to ensure that a large sample of residents could potentially be affected by the vibrations. For this reason, light-railway construction operations have been chosen as sources for determining both exposure and annoyance in the living environment.

The particularity of railway construction is that it can be modeled as a linear process: 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 the same exposure would occur at other points on the line where surveys could take place independently of the measurements. In the following section a description of the measurement approach is given.

MEASUREMENT APPROACH

With permanent sources, like rail, it is possible to estimate exposure from internal measurements in the homes of survey respondents[9]. 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.

In fact the measurement methodology relies on field work where long term measurements are combined with external array and internal measurements in order to assess the exposure across the entire living environment. The exposure measurements are presented in 1.1, the overview of the measurement sites is given in 1.2 and the life cycle of the construction process is presented in 1.3.

1.1 Exposure measurements

Taking advantage of the linearity of the construction process, measurements are performed at a fixed location on one segment of the site as the work passes by. The elements of the measurement approach are:

- Long term measurement or control position
- Internal measurement
- External array measurements

The purpose of the control position is to capture the entire life cycle of the vibration exposure. It is generally placed at the boundary between the residential environment and the construction site lasting for a period of weeks.

Internal measurements are carried out over a short period, at least half an hour, for evaluating the impact of the vibration activity within the respondent's property as close as possible the 'point of entry' of the vibration into the body.

External arrays enable simultaneous measurements of the vibration at various distances from the source. These measurements are used for evaluating properties of the soil and thereby to obtain a prediction of the exposure at any distance from the long term monitoring position. The development of the exposure propagation method is described in section 0.

The vibration measurements were performed using gps time synchronized, strong motion, force feedback accelerometers: the Guralp CMG-5TD[10].

Array and internal measurements are, by necessity, short term and are therefore timed by discussion with construction manager to take place during the day of maximum activity. In this way the signal to noise ratio is as high as possible.

In the planning of the measurement campaign, for both exposure and response, it is vital to collaborate with the construction manager in order to obtain the following information: the time schedule of the operation involved in the construction yard, the identification of the operations that may cause more annoyance and the most suitable areas of the construction line for conducting both exposure and response measurement.

1.2 Overview of measurement site

A description of the measurement site is needed to understand the type of construction work that affects the living environment, the operations involved in the process and the definition of the reference system in order to calculate the distances of the measurement positions from the vibration sources considered.

In order to derive the exposure-response relationship, two construction sites have been surveyed: the so called construction site A and site B. The aim of the works in site A was the reconversion of an old railway line to a light rail line and 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. At site B construction works were carried out for a light rail installation in a residential street. The operations performed were saw cutting, pavement breaking/shallow excavation and compaction.

The measurement setup for site A is shown in

Table 2 - - Normal Distances between the measurement positions and the origin of the reference system (in meter)

M1	M2	M3	M4
14	23	32	42

Table 3 - Summary of vibration exposure descriptors considered. Where $\ddot{x}(n)$ *an acceleration time series, N is the number of samples in the acceleration time series, and T is the duration of the event in seconds.*

Exposure Metric	Calculation
Peak particle acceleration (m/s^2)	Maximum deviation of the time series from the mean
Root mean square (m/s^2)	$\ddot{x}_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^2}$
Vibration dose value (m/s$^{1.75}$)	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
Root mean quad (m/s^2)	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$

Table 4 - Pseudo attenuation coefficient per weigthed W_b *(W) vibration exposure metrics*

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

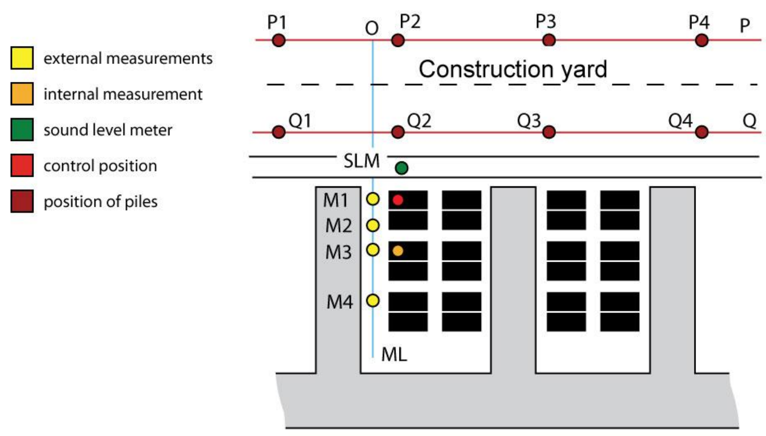

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

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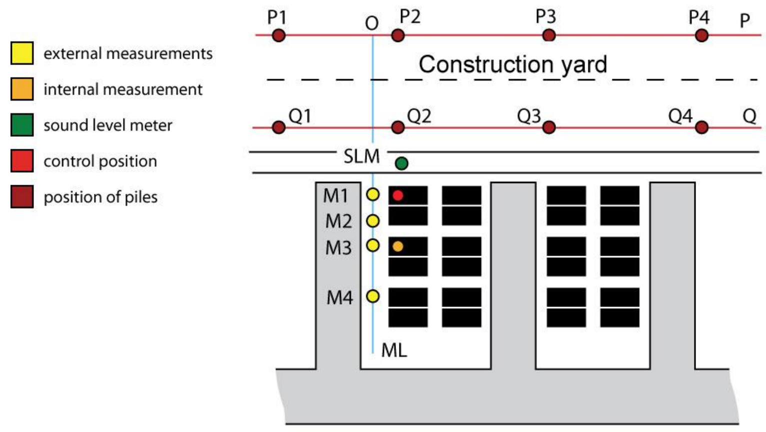

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

) whereas the distances between the pile positions identified on the line P and the measurement points (yellow points in

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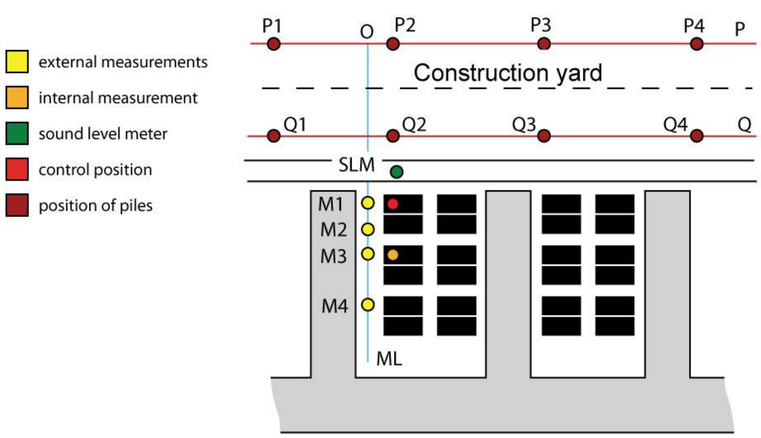

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

) has been quantified in Table 1. The control position is at 6 meters from the line Q.

The measurement setup in site B is shown in Figure 2. The datum is taken as line O (Figure 2). The normal distances to line O of the external measurement points are shown in Table 2. The control position is at 14 meters from the line O.

1.3 Life cycle construction activity

The daily exposure is the amount of vibration to which the resident is exposed during the construction work every day. The daily exposure is expressed in terms of VDV in the z direction W_b weighted over a 10 hour time window, from 8 a.m. to 6 p.m., which represents the typical hours of work for construction during a week day.

The life cycle of the construction activity shows, for each measurement site, the evolution of the daily exposure during the long term monitoring period, 63 days at site A and 36 days at site B, in order to identify the maximum caused by the construction operations.

In Figure 3 the life cycle for Site A is plotted: the maximum daily value is reached at the 22nd day of monitoring with a maximum value of 0.22 m/s$^{1.75}$ recorded when a pile was driven at position Q2 (see

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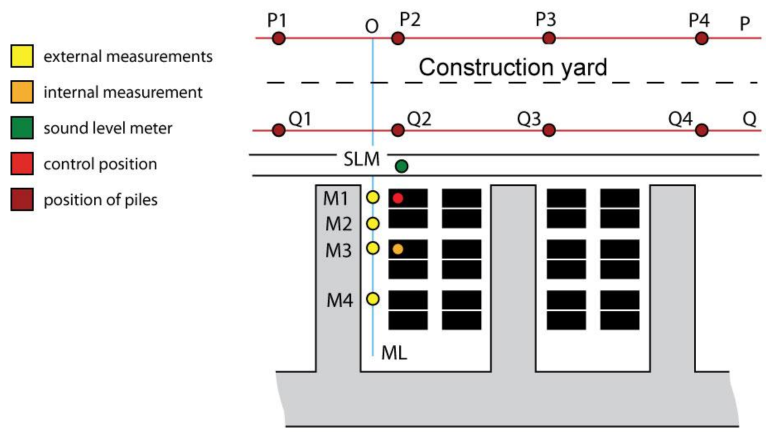

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

) very close to the control position. On the other hand, the life cycle for the Site B, Figure 4, shows that the maximum daily exposure due to pavement breaking and shallow excavation is reached at the 4^{th} day of monitoring with 0.09 $m/s^{1.75}$. The highest peak, occurring on the 24^{th} monitoring day, is probably due to compaction activity.

EXPOSURE PROPAGATION

In this section the development of the method for predicting the vibration exposure at different distances from the construction site is described. The result is achieved using the well known semi-empirical relationship used in construction as "propagator" of the vibration exposure. The underlying theory and assumption are first presented (See section 1.4). The method of obtaining damping factors for the soil from the external array measurements is then described in section 1.5 and the model validation is in 1.6.

1.4 Modeling propagation

The main aim of the array measurements was to derive a propagation law for each measurement site using one of the semi empirical relationships presented in the literature. This approach is very common in construction and example 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[4] and in Woods[1] for piling vibrations. Those relationships can be applied only if a complete set of parameters related to the source are known but the latter were not available for either of the sites surveyed during the field work. As a consequence, the most common distance attenuation relationship in literature was used: the Barkan's Law[11].

$$A(d) = A_0 \sqrt{\frac{d_0}{d}} e^{-\alpha(d-d_0)} \qquad (1)$$

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 fixed the material damping α. The equation (1) has been used for fitting the experimental decay obtained in the array measurements for an empirical estimation of the material damping. The assumptions made are that the soil is considered an elastic half space and that the propagation is dominated by Rayleigh waves. According to Richard et al.[12] the propagation assumption is realistic whereas the assumption of elastic half space is considered an idealization because the soil is layered in real conditions.

The α -value obtained is then substituted into Barkan's law yielding a model for prediction of the vibration exposure at any distance from the long term monitoring position.

1.5 Soil properties

The experimental fit with Eqn(1) is shown for the Site A in Figure 5. Barkan's law was applied considering only the contributions of the piling operations coming from P1 and P2 positions (see

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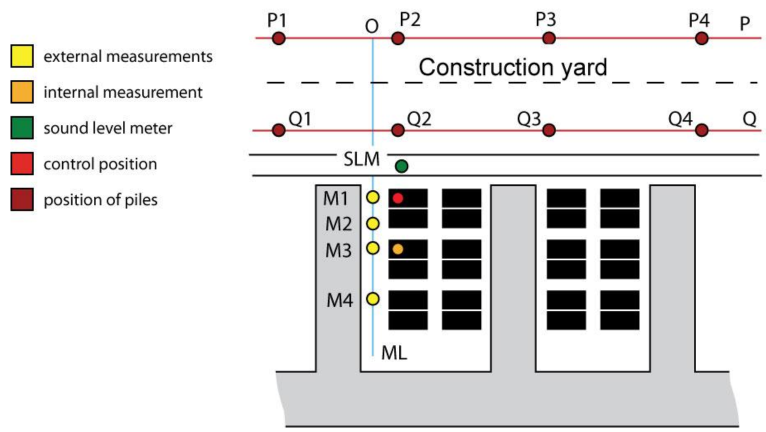

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

). In fact, positions P3 and P4 were ignored because of shielding from the measurement array by a row of houses whose cellars were assumed to be acting as wave barriers and therefore causing attenuation of vibration. The fit of the experimental data provided an α = 0.0250 for site A.

A similar analysis was carried out for site B (see Figure 6). It should be considered that the vibration sources for site B were far less localized 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 provided an α = 0.0379 for site B.

The relationship seems to provide reasonable results in the description of the propagation of the external vibration with a light overestimation when the distance is greater than 30 *m* due to the daily variation of the construction sources[13].

Further insight into the reliability of the results can be gained by carrying out an octave band analysis. The approach is essentially the same as that reported above but is carried out using vibration data that is pre-filtered in octave bands, similar to the one used by Amick[14]. In this way we should be able to quantify the frequency dependence of the material damping[15]. The results of this analysis will be presented in another article.

1.6 Validation

As said in section 4.1 the alfa value obtained by the array measurement, section 4.2, needs to be substituted into Barkan's law yielding a model for prediction of the vibration exposure at any distance from the long term monitoring position. The prediction model for the exposure metric *M* is shown in Eqn(2):

$$M(d) = M_{CP}\sqrt{\frac{d_{CP}}{d}}e^{-\alpha_M(d-d_{CP})} \tag{2}$$

Where $M(d)$ is the metric at distance d from the source and M_{CP} is the metric evaluated at d_{CP} from the source and α_M is a pseudo attenuation coefficient. The metrics considered in this case will be: weighted peak particle acceleration (PPA), weighted rms acceleration, VDV and weighted root mean quad (rmq) acceleration. They are shown in Table 3 and calculated with respect to the z component of the acceleration applying the W_b weighting.

Two characteristics of the model need to be tested: its accuracy in the propagation of the metrics and the goodness of the control position as predictor of external vibration exposure.

The accuracy of the model can be evaluated considering the decay of the exposure metrics from the array measurements and comparing the pseudo attenuation coefficient obtained using Eqn(2) with the one found in section 4.2. The α_M for the site A are reported in Table 4.

If the evaluation of the percentage relative error between the pseudo attenuation coefficients of the exposure metrics and the attenuation coefficient is made, it can be seen that a maximum underestimation of 30% of the pseudo coefficients is obtained for the weighted RMS. The minimum is for the PPA and RMQ around 16%. Within these limits, it can be assumed that Barkan's law with the soil properties obtained in section 4.2 can be used for describing the propagation of all the metrics across the living environment. Similar results have been found for site B. The goodness of the control position as predictor of external vibration exposure needs to be evaluated as well. The results presented in Sica et al.[13] show that in the worst case scenario represented when the vibration source is in front of the house; the control position is a good predictor of the external exposure but an uncertainty need to be associated at the moving nature of the source.

EXPOSURE ASSESSMENT

The exposure is assessed from the control position data and then propagated to the appropriate distance using Barkan's Law Eqn(2) with the empirical attenuation parameter identified from the array measurements in section 1.5. If an internal exposure is required then it is necessary to apply the external-to-internal transmissibility. The latter can be provided as a single figure amplification ratio as done in work the of Martin[16]. The methodology has been tested also for assessing the internal exposure providing interesting result but it cannot be validated due to the lack of internal measurements[13]. For this reason, there is greater confidence in the estimates of external vibration for the construction sites. Results are presented in the next section.

RESULTS

In this section we present the prediction curves used to evaluate the exposure from railway construction sources. Due to absence of definitive information on the time period over which the exposure should be calculated[13], the results are shown in two ways: the maximum daily exposure caused by a single construction operation and the total exposure over the period of long term monitoring. From the analysis of the life cycle of the construction process presented in section 1.3, the construction operations generating the highest daily exposure are: piling operations for site A and breaking/shallow excavation for site B. In Figure 7, the decay of the external VDV (z component) with distance for both operations is presented.

As the vibration exposure is a cumulative value, the total vibration exposure, during the typical hours of work for construction, has been calculated for both sites during the entire long term monitoring period. For site A, a total VDV (z component) of 0.27 $m/s^{1.75}$ was calculated over 62 days of monitoring whereas for site B the value was 0.19 $m/s^{1.75}$ over 37 days of monitoring. The values obtained have been propagated from the control positions using Barkan's law, Eqn(2), with the soil properties estimated in 1.5. The results are shown for both sites in Figure 8. The curves in Figure 8 combined with the annoyance data, gathered through questionnaires, have been used to build the exposure response relationship for construction sources presented in Woodcock et al.[17].

CONCLUSIONS

The transitory nature of construction vibration makes it difficult to develop a measurement methodology based on an intensive field work for measuring the internal exposure as the case of semi permanent sources like railway[9]. The survey has been conducted using light railway construction. The construction process can be seen as linear because the same operations are repeated along the length of the track, thereby causing similar vibration exposure in a variety of residential areas. In this scenario social survey and vibration teams worked independently.

The estimation of the exposure for construction relies on external measurements in an array configuration, supported by a semi empirical prediction model for propagating the measured exposure from the long term monitoring position, placed at the boundary between the construction site and the living environment, to residences at different distances.

For the measurement sites considered, a maximum overestimation of 30% has been found for the propagation of the exposure metrics from the control position using the Barkan's law with the soil property found with the external array measurement.

Further research is needed for the validation of the methodology in the assessment of the internal exposure. Since the propagation model considers just the contribution of Rayleigh waves, an improvement is needed taking all the wave types generated by the vibration source.

With this methodology, the first exposure response relationship has been derived for a "non-steady state" problem. The latter is very important in order to evaluate the community response to vibration in a situation where the source is starting to affect the living environment.

In fact, according to Woodcock et al.[17], residents exposed to the same vibration level are more annoyed by a "non-steady state" problem (rail construction) with respect to a "steady state" one (rail traffic).

ACKNOWLEDGEMENTS

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Table 1 - Distances between pile positions and measurement positions (in meter)

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

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

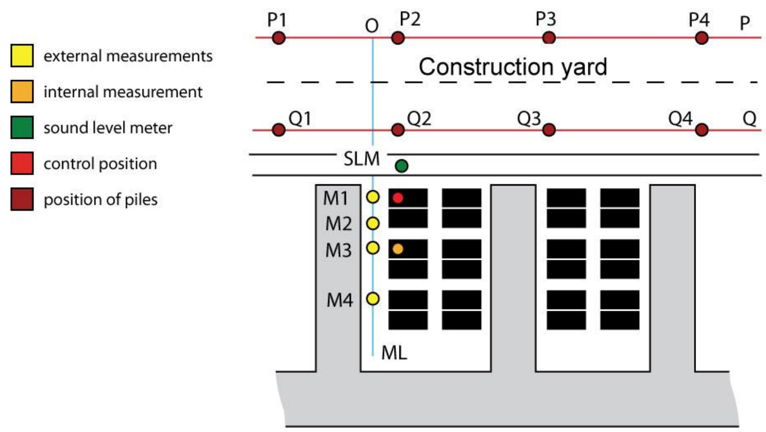

Figure 1 - Measurement setup site A. Line Q in red origin of the reference system. External measurement point yellow dot. Control position red dot. Internal measurement orange dot.

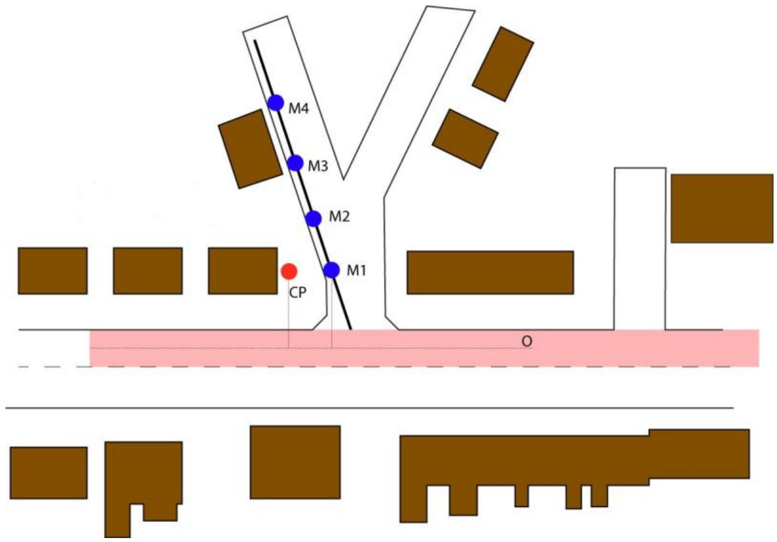

Figure 2 - Measurement setup site B. Line O in black origin of the reference system. External measurement point blue dot. Control position red dot.

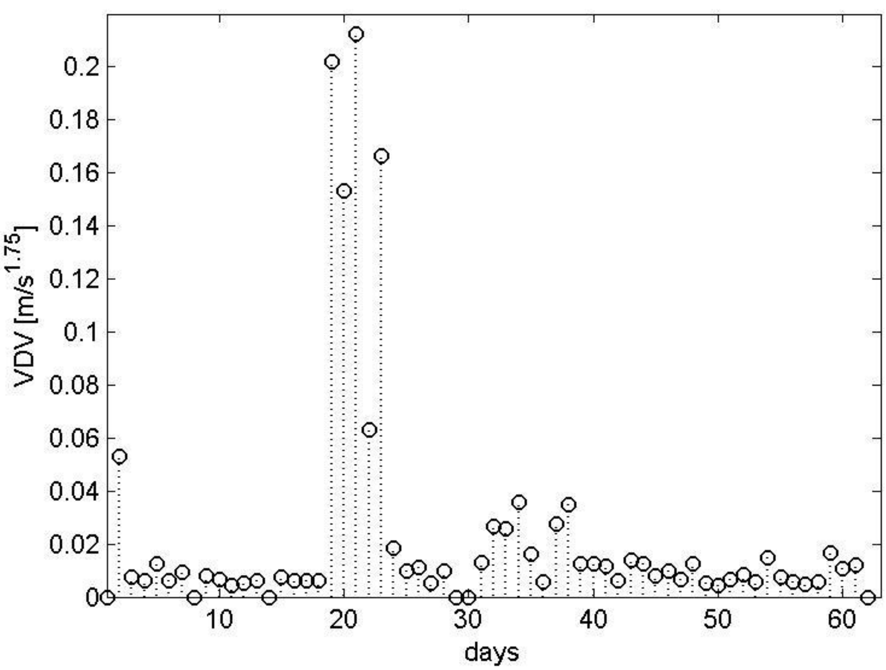

Figure 3 - Site A VDV (z component Weighted W_b) over 10 hours vs monitoring days. Lifecycle of the construction activity

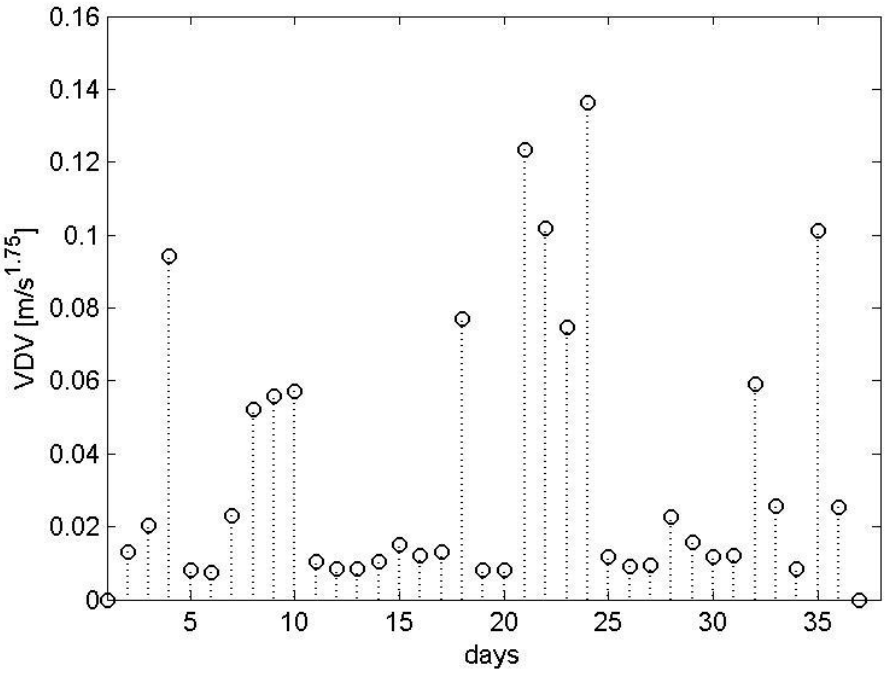

Figure 4 - Site B VDV (z component Weighted W_b) over 10 hours vs monitoring days. Lifecycle of the construction activity

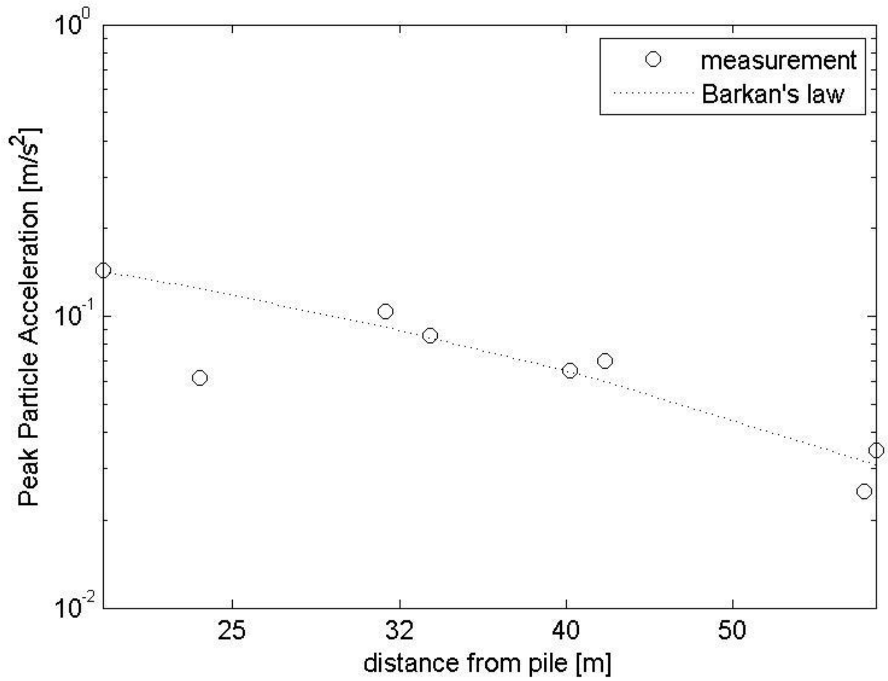

Figure 5 - Site A Peak Particle Acceleration (z component) vs distance from pile (only contribution P1 and P2).Measured Point (dot) Experimental fit with Barkan's Law (line). Graph in log scale

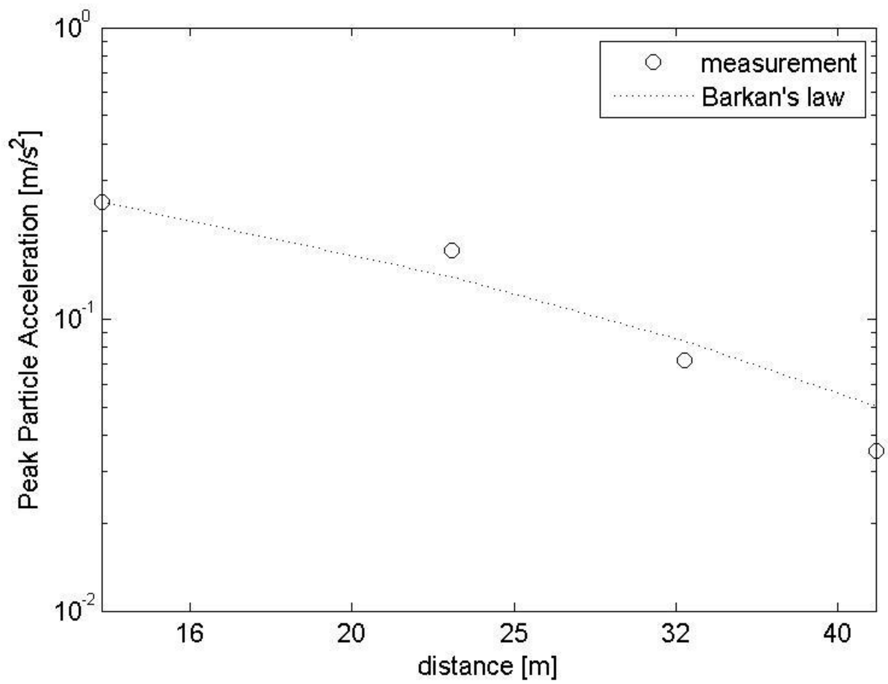

Figure 6 - Site B Peak Particle Acceleration (z component) vs distance from pile (only contribution P1 and P2).Measured Point (dot) Experimental fit with Barkan's Law (line). Graph in log scale

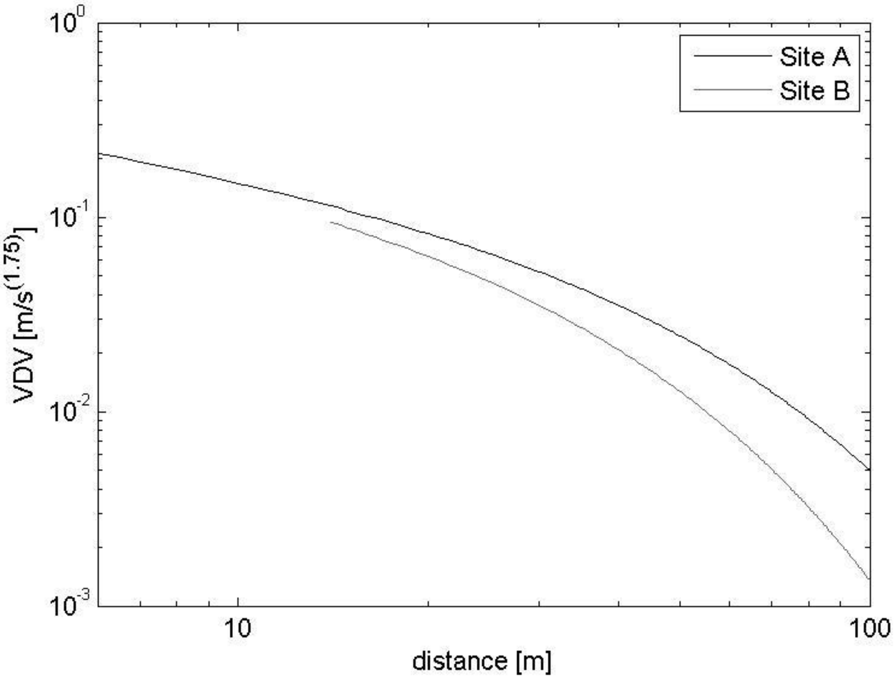

Figure 7 - VDV (z component) vs distance. External Maximum daily exposure from control position with Barkan's Law.Site A (Black line) piling operation Site B (grey line) pavement breaking/shallow excavation. Daily Exposure calculates over 10 hours. Graph log scale

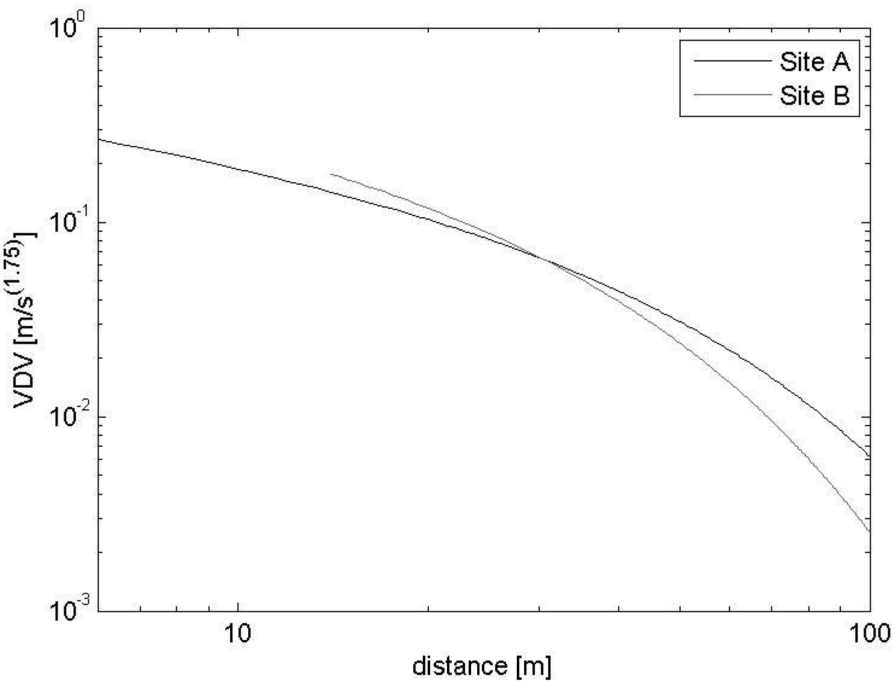

Figure 8 - VDV (z component) vs distance. Total External Exposure propagated from CP with Barkan's Law. Site A (black line) exposure calculated over 62 days. Site B (grey line) exposure calculated over 37 days. Graph log scale