Estimation of vibration exposure in residential environments

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ABSTRACT

The University of Salford has derived an exposure-response relationship for vibration in residential environments. Vibration measurements have been used for assessing the human exposure alongside a social study questionnaire based on face-to-face interviews for quantifying the human response. This paper deals with the exposure side of the study. In order to cover the wide range of exposures affecting the living environment, various types of vibration activity have been measured, namely: railway, construction and domestic activity. Different and novel measurement approaches have been adopted for assessing the internal vibration exposure in almost 1,000 dwellings. This paper describes the methodologies used for deriving the estimate of the exposure for each vibration source considered and also provides some results. [Work funded by the Department for Environment, Food and Rural Affairs (Defra) UK]

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 of their control, assuming that they remain indoors during the period of exposure. Different types of vibration may affect a living environment and can be grouped in the following categories (BSI 2008): transient, continuous and random.

For providing the wide range of exposure affecting the residential environment, in the framework of the Defra project "Human Response to Vibration in Residential Environment" (Waddington et al. 2011), different vibration sources have been considered, specifically: railway activity, construction activity and internal or domestic activity.

In order to develop an exposure-response relationship a high number of case studies are needed. A total of 1,431 case studies were made, including 931 for railway, 350 for construction and 150 for internal vibration sources. In this scenario the living environment has been defined as the dense group of dwellings within a radius of 100 meters from the vibration source for increasing both the range of the exposure and the potential number of respondents. It can be helpful to break down the vibration propagation through the residential environment in 4 areas identified as: source, path, receiver and human body.

The vibration perceived by the human body at the 'point of entry' (contact surface between the human body and the vibrating receiver) is due to the complex interaction of the vibration created at the source with the other areas identified above. Each of these regions can amplify or reduce the frequency content of the vibration source. Therefore, these factors need to be taken into account for a complete understanding and estimation of the exposure.

Vibration sources can affect the residential environment in a more or less permanent way, like railway traffic, or in a transitory way such as vibration from a construction site. 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 both the measurement and calculation of exposure and in the coordination with the social team in charge of the measurement of response.

In order to estimate the exposure from the sources considered in the study different methodologies have been developed. The latter are described in the following section.

METHODOLOGIES

For evaluating the 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 its temporal characteristic such as repeatability.

The vibration exposure is generally quantified with a weighted energy average descriptor such as rms velocity for continuous or random vibration, and for impulsive sources of vibration, peak particle velocity or acceleration is used. However, BS 6472-1 adopts an dose-based exposure metric that can be used for assessing exposure for any type of vibration: the Vibration Dose Value ($VDV_{b/d,day/night}$).

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

where $a_w(t)$ is the frequency-weighted acceleration measured (in ms^{-2}), using W_b or W_d as appropriate; and T is the period (in *s*) during which the vibration occurs.

In the framework of the project “Human Response to Vibration in Residential Environments”, the human exposure has been evaluated with measurements, so different source specific methodologies have been created for the measurement (Peris et al. 2011) and the estimation (Sica et al. 2011) of the exposure with different metrics.

The environmental vibrations were measured in the field using a Guralp CMG-5TD (Guralp 2007) strong motion tri axial accelerometer with a low pass filter at 100 Hz. The instrument is a force feedback transducer with low noise floor associated (~10μ ms^{-2} across the frequency range of interest) and an in-built 24-bit digitizer. The ease of use of the system, and the ability to synchronize multiple units via GPS allowing phase-locked measurements, made these accelerometers ideal for this project.

The estimation of the exposure relies on two measurement types: long term measurement and short term measurement. Long term measurement with a minimum duration of 24 hours is used for characterizing the activity of the vibration source. Single short term measurement, usually with an average duration of 30 minutes, has been used for evaluating the impact of the vibration within the respondent property as close as possible to the point of entry. External short term measurements with accelerometers arranged in an array configuration were also used for assessing the vibration attenuation through the residential environment.

The source specific methodologies are presented in the following sub sections.

Exposure from railway vibration

Railway activity is considered a random vibration source that acts external to the residential environment. Furthermore, railway vibration affects the residential environment in a semi-permanent way. The semi-permanent nature of the source made it possible for the social survey team to arrive on site ahead the vibration team, conducting as many interviews as possible (Condie et al. 2011). Before visiting the site, the vibration team booked an appointment with the respondents who had agreed to have an internal measurement. According to BS 6472-1 the internal measurement should last at least 24 hours in order to determine the full vibration exposure. However, this could not practically be achieved, due to the huge extent of the survey (931 case studies); therefore an alternative measurement procedure was implemented (Woodcock et al. 2009) meeting “half way” the needs of both project and standard. The measurement procedure can be summarized in the following points:

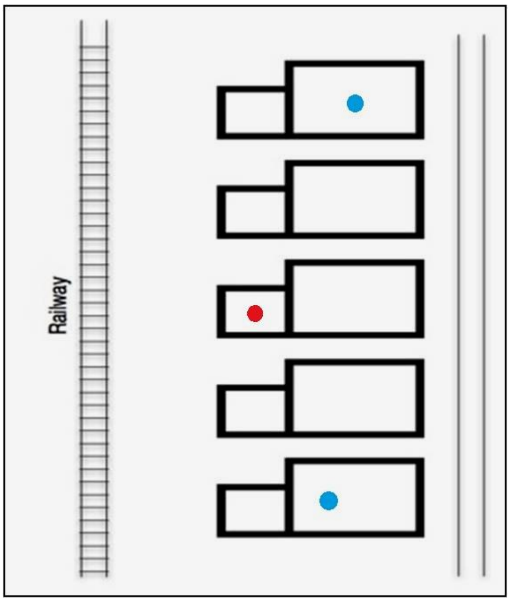

Figure 2: Overview railway site

1. 24 hour long term monitoring measurement (control position) in proximity of the residential properties (red dot Figure 2).
2. Synchronized short term monitoring measurement within the property as close to the point of entry as possible (blue dot Figure 2).
3. Calculation of control-to-internal velocity ratio.
4. Calculation of the long term exposure from the results of 1 and 3.

During the long term monitoring period, the vibration team collected as many internal measurements as possible. For each of these cases the measured velocity ratio, obtained by averaging over a few train passages (generally more than six), was used as a filter for scaling the activity recorded at the control position inside the respondent’s property. In this way, a 24 hour estimate of internal vibration activity was obtained from which various exposures could be evaluated.

The success of the methodology can be judged by the fact that an internal measurement was made for 56 % of the properties at which interviews were obtained. In this way a good sampling of the internal vibration activity in the measurement sites was achieved. The estimation of the exposure for the case studies where internal measurements weren't allowed was based on the internal exposure obtained from measurement inside a nearby property of a similar type and at a similar distance from the railway. This kind of estimation was thought to be more reliable than those obtained from external measurements outside the property.

Exposure from construction activity

Construction activity can generate different types of vibration depending on the operation involved in the construction process. According to Wiss (1981), the vibration generated by construction sources is of a character that may potentially affect residents. As for railways, construction vibration is generated externally to the living environment but it has a transitory character.

In order to assess exposure and annoyance it is important to consider the size of the construction site and the duration of the work to ensure that a large sample of the residents should potentially be affected by the vibration. For this reason the operations from light-railway construction has been chosen as sources for determining the exposure in the living environment.

This specific source consists of a set of operations that are carried out in sections along a line. When the section is complete the vibration source moves to another point along the line. Logistically, the approach used for railway (the social survey must be conducted before the vibration measurements in order to avoid biased responses) cannot be adopted: but for transient sources, the survey 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.

In this scenario the social and vibration teams worked independently. The response measurements were undertaken along the parts of the line where the activity was already finished, whereas the exposure was measured before, during and after the work with the assumption that the same exposure would occur at the other point of the line.

The methodology for the determination of the exposure is based on long term monitoring (or the control position, red dot in Figure 3) as close as possible to the boundary between the construction yard and the residential environment for recording the entire life cycle of the construction operations which required 62 and 37 days respectively on two different sites.

Controlled experiments based on array measurements (yellow dots in Figure 3) have been used for quantifying the attenuation of the vibration exposure across the residential environment caused by, according with the construction manager, the major activity of the construction operation. During the controlled experiment, a few internal measurements (orange dot in Figure 3) were taken for evaluating the internal exposure for the property types present in the residential environment.

The exposure recorded at the control position was propagated to other positions using the semi empirical propagation relationship with the attenuation parameter obtained in the controlled experiment.

Unlike the railway case the daily exposure from construction has been quantified over the duration of the works, i.e. between 8 a.m. and 6 p.m. and not over 24 hours.

Since the exposure from construction activity is a combination of the exposures from different operations, the maximum daily exposure occurring during the construction works has been used to quantify the exposure. An alternative approach would be to define a cumulative exposure over the entire duration of the works.

Exposure from internal activity

Internal sources were defined as the set of vibration sources acting inside the residential property, such as those that are caused by mechanical excitation like washing machines or by human activity itself providing either continuous or transitory types of vibration.

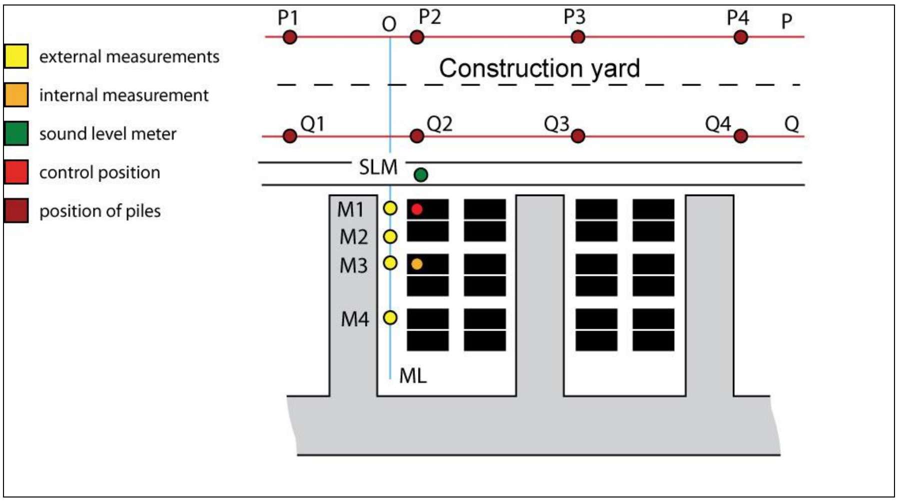

Figure 3: Overview construction site

The possibility that internal sources can be felt by residents is given by a combination of factors related to the frequency source and the resonance frequency and damping of the structural elements that propagate the vibration through the building. For these reasons, it seems that this problem is likely to be felt in high rise building or 'lively buildings' (Sylvestre-Williams et al. 2010).

Due to privacy issues it was not possible to gain access to 'lively building's therefore the measurements were performed where permission was available including university accommodation and sheltered accommodation managed by local authorities.

In this case the coordination between the social and vibration teams was similar to that for the railway case. The exposure measurement relies on synchronized long term monitoring (24 hours) in different parts of the building. Ideally the measurements were conducted in empty apartments to ensure that the living environment received only vibration from its surroundings. The exposure is calculated over the long term monitoring period.

RESULTS

In this section some results of the exposure estimation for the source specific methodologies are presented.

In the railway case an estimation of the internal exposure is obtained for each case study providing a "one to one" relationship with the annoyance. Therefore, the direct consequence of this method is the exposure response relationship for the population affected by railway vibration reported in Woodcock et al. (2011).

The methodology used for construction vibration relies on a semi empirical attenuation-distance relationship of the vibration exposure across the living environment. In Figure 4 the decay with the distance of the total external vibration exposure expressed in VDV (z component W_b weighting) is shown for the two construction sites used in our study.

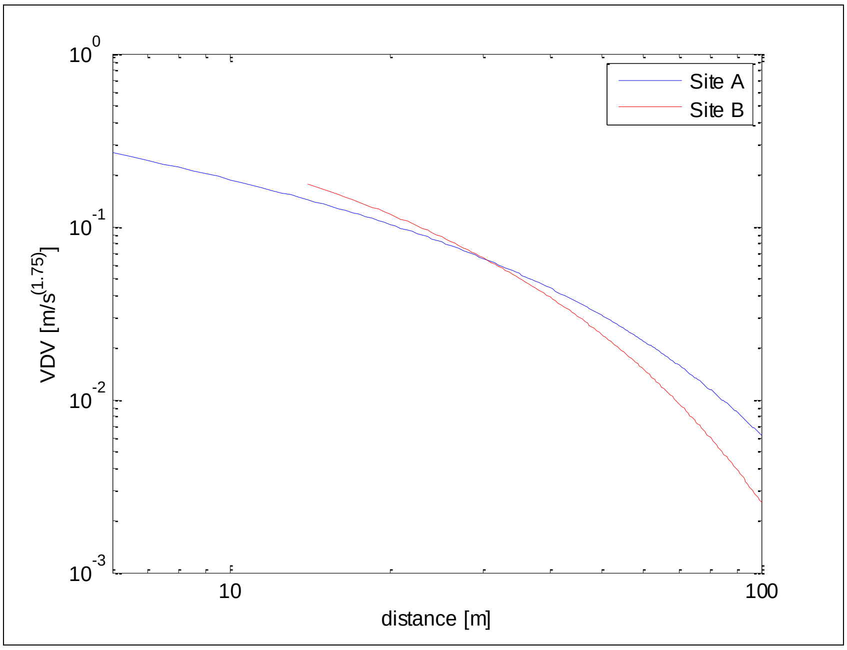

Figure 4: VDV (z component) vs distance. Total external exposure propagated from the long term monitoring position. Site A (blue line) exposure calculated over 62 days. Site B (red line) exposure calculated over 37 days. Graph in logarithmic scale

For internal sources, the procedure estimated the exposure from long term 24 hour internal measurements in different parts of the building considered for the study. In Table 1 the level of exposure expressed in VDV (z component W_b weighting) is reported for the different floors of a university accommodation block. The difference in exposure between the ground floor and the other floors can be linked to the fact that the ground floor is the entrance of the building, so it might be possible that the amount of internal vibrations generated, for example by footsteps and door slams, are higher in comparison with the other floors of the building.

Table 1: VDV (z component) vs floor. Exposure calculated over 24 hours

Floor	VDV
G. Floor	0.3
1st Floor	0.025
2nd Floor	0.027

CONCLUSION

Different methodologies for estimating the exposure from vibration sources in residential environments have been presented, suitable for providing data for deriving exposure response relationships. The different nature of the source considered (railway, construction and internal activity) required distinct strategies for measurement and estimation of the exposure, but also a different coordination was needed between the teams in charge of measuring both the exposure and the response.

The quasi static nature of railway activity has permitted synchronization with the social survey, and a large number of internal measurements have been collected. The methodology relies on a 24 hour long term measuring position and synchronized snapshot measurement within the respondent's property. The average velocity ratio between the two measurement positions has been used for scaling the activity recorded at the control position inside the property, so an estimation of the internal 24 hours exposure is obtained. Furthermore, the high proportion of internal measurements (53 % of 931 case studies) has also permitted estimation of the exposure for the case studies where it was no internal measurement was possible.

Unlike railway vibration, an intensive survey of internal measurements was not possible for construction activity, due to its transitory nature. 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. In this scenario, the social 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 propagation of the measured exposure from the long term monitoring position, placed at the boundary between the construction yard and the living environment, to residences at different distances.

Internal sources are identified as the mechanical and human excitation created inside the property. They can be transitory or static depending on the nature of the excitation. 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. The latter concentrated on university and sheltered accommodation where easy access was possible. The coordination among the teams was the same as for the railway case, and the estimation of the exposure is based on long term internal measurements on each floor of the building.

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