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EXPERIENCE IN USING BS 6472 TO ASSESS NUISANCE FROM VIBRATION

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1. INTRODUCTION

The Government's planning advice on noise to planning authorities in England and Wales indicates that vibration may also have to be considered for certain types of noise source. This includes roads and railways. Many planning authorities require a vibration assessment to be carried out as part of planning applications for residential development near vibration sources, particularly railways. The authors have carried out many such assessments over the years. The paper discusses the various techniques that have been employed to measure vibration according to the relevant British Standards, including BS 6472. The various types of measuring equipment available and how they are used are described, as are the best methods of mounting monitoring transducers. Measurements are often made on a site before housing is present and predictions have to be made of levels to be expected in completed dwellings. There is a discussion of typical amplifications and attenuations between levels in the ground surface, in foundations and on higher floors. Ways of predicting long term vibration levels from short-term measurements are described. Case studies are given showing the typical applications of the assessment procedure.

2. BRITISH STANDARDS FOR ENVIRONMENTAL VIBRATION

A number of British Standards relate to, or contain guidance on, the measurement and assessment of environmental vibration. BS 7385 [1] is concerned exclusively with the measurement and assessment of vibration affecting building structures and does not extend to the assessment of vibration as a nuisance. However, it does contain useful guidance on equipment requirements and measurement practice.

BS 5228 [2], in Parts 3 to 5, discusses vibration from opencast coal extraction, piling operations, and surface mineral extraction, providing good practice methods for reducing noise and vibration from these sources. It does also give some guidance on measurement and assessment, although generally refers to other British Standards, and supplies some useful information on predicting vibration. Part 4 states the human threshold of perception of vibration is typically 0.15 mm/s to 0.3 mm/s and 'vibrations above these values can disturb, startle, cause annoyance or interfere with work activities. At higher levels they can be described as unpleasant or even painful'. It does not provide any further numerical guidance for the assessment of vibration effects, apart from a table of parameters to measure and the sensitivity of equipment to use.

BS 6472:1992 [3] provides guidance on human response to building vibration, including tentative guidance on the magnitudes of vibration at which adverse comment may begin to arise. It provides methods for assessing the response to impulsive vibration (short events less than two seconds, such as blasting), continuous vibration (uninterrupted for a daytime period or night time period, such as some road traffic), and intermittent vibration (such as from a railway). For impulsive vibration it advocates the use of peak particle velocity (ppv), for continuous and intermittent vibration it introduces the concept of the vibration dose value (VDV) and the total VDV for the day or night period is assessed. A procedure is described to relate the severity of intermittent vibration to that of continuous vibration.

3. VIBRATION MEASUREMENT

3.1 Equipment

The procedures in BS 6472 for calculating the estimated VDV (eVDV) require the vibration to be measured in terms of the r.m.s. frequency-weighted acceleration. The frequency weighting curves are defined in the Standard, and are implemented as filters in suitable measurement equipment.

One measurement technique is to record unfiltered time histories of the vibration from which any desired value can later be determined. Alternatively, some vibration meters include the necessary weighting networks, to enable weighted acceleration to be measured directly in the field. An example of this is the Brüel & Kjær 2511 vibration meter with WH0454 modification. This system only allows measurement in one axis at a time. Some digital systems allow triaxial measurement and storage of both linear and weighted values.

An alternative technique is to record the VDV of an event, or for a set period, directly. Examples of equipment which enable this include a Brüel & Kjær system, comprising the 2522 human vibration unit connected to a 2231 sound level meter with WB1145 vibration event module loaded; and the Vibrock V801 vibration dose meter. The Brüel & Kjær system is designed to measure and log the VDV of vibration events using a set level threshold or manual trigger. A measurement time period cannot be set, but instead an 'event' lasting for the required duration can be manually started and stopped. The V801 measures the VDV over any period, predicts the daytime and night time period VDVs for runs less than 16 hours and 8 hours, and measures the true period values for longer runs. Both sets of equipment measure in all three axes simultaneously.

3.2 Measurement Location

BS 6472 recommends that the measurements should ideally be conducted at the point of entry to the human subject, or on a building structural surface supporting a human body. It acknowledges that in some circumstances, measurements may have to be made outside the structure on or some other surface, but in these instances the transfer function should be allowed for. Guidelines for transfer functions are discussed in Section 5 of this paper.

For residential buildings there will be numerous points of entry of vibration to the occupants. It is therefore sufficient to measure the vibration at a few generalised positions. Guidance is given in [1] and [2]. Measurements should be undertaken on the foundations, the ground outside, on the ground floor and upper floor of the building, and - for multi-storey buildings - every four floors. Additional specific locations may be required following complaints, for example.

If access to the foundations proper are not possible it is typical to measure at a point low on the main load-bearing external wall facing the source at ground floor level. A masonry threshold set into the external wall is a good example of this; care must be taken if siting the transducers on sills inside windows, to ensure that the flexibility of the wood/uPVC does not affect the measurements.

For proposed development sites, where buildings do not currently exist, it is usual to measure at the location of the closest proposed façades to the vibration source. If the vibration is severe, it may be informative to measure at further known distances back to gain an understanding of the decay rate with distance for that particular site.

3.3 Transducer Mounting

There are many methods of attaching transducers [see 1], and size and weight are determining factors. The method used must enable the transducer to accurately reproduce the movement of the element, and for this it must be rigidly attached.

The accelerometer(s) are usually mounted on a metal cube or in a small metal box to enable attachment to vertical and horizontal surfaces. For vertical surfaces, such as a structural wall, it is ideal to drill a small hole to take suitable expansion bolts or to glue in a threaded stud with epoxy resin. In many instances this is not possible so horizontal attachment is necessary. As most vibration from road and railways will be significantly less than 9.8 m/s^2 (1g) the block can simply be sat on a suitable surface. Tri-spiked mounting bases give more rigid seating and allow some penetration of thin resilient surfaces. The base should be adjusted to be level in all axes.

For development sites with no existing buildings the transducers must be mounted to the ground. Measurement on the loose soil surface will generally result in elevated results due to coupling distortion. In order to reduce this, the transducers should either be buried deeply in the ground (for which the transducers should be corrosion resistant and designed for the purpose) or mounted on a rigid surface plate. A suitable rigid surface plate for most applications is a well-bedded paving slab [see 1]; ideally measurements may be undertaken on an existing tarmac pavement, if present on site at a suitable location. Note that some paved paths have loosely laid slabs which would lead to false measurements.

Some engineers advocate the use of a spike driven into the ground with the transducers mounted on top. Unless care is taken horizontal and rotational movement may occur which would affect the measurements.

Normal low rise dwellings are built on strip footings where trenches are excavated through the organic topsoil to more stable load bearing strata. In our experience, vibration levels can be lower on these strata. In the case of peaty topsoil they can be much lower. In these cases it is preferable to excavate down to the load bearing strata to make the measurements. If site investigation involving trial pitting is being carried out, the vibration measurements can often be conveniently carried out at the same time.

4. DETERMINATION OF VIBRATION DOSE VALUE (VDV)

4.1 Definition

The Vibration Dose Value is defined as:

$$\mathrm{VDV} = \left(\int_0^T a^4(t)\,\mathrm{d}t \right)^{0.25} \qquad -\{1\}$$

where VDV is the vibration dose value (in $m/s^{1.75}$); $a(t)$ is the frequency-weighted acceleration; T is the total period of the day (in seconds) during which vibration may occur.

The VDV has a fourth power time dependency, ie to double the VDV requires either a doubling of the acceleration or a 16-fold increase in the duration of exposure.

4.2 Practical Calculation

The crest factor of a vibration signal is the peak value divided by the r.m.s. value. For vibration with a low crest factor, such as road and railway vibration, the total VDV for the day can be approximately given by:

$$\text{eVDV} = 1.4 \times a(\text{r.m.s.}) \times t^{0.25} \qquad \text{- \{2\}}$$

where eVDV is the estimated vibration dose value (in $m/s^{1.75}$); a(r.m.s.) is the measured r.m.s. frequency-weighted acceleration (in m/s^2); t is the total duration of vibration exposure (in seconds).

The 1.4 multiplication factor has been determined empirically and approximates the measured root-mean-square acceleration to root-mean-quad (r.m.q.) acceleration.

4.2.1 VDV of Railway Vibration

To estimate the VDV at a receiver close to a railway a measurement survey would be conducted to obtain values of a(r.m.s.) and the pass-by durations of a representative number of train events. As a rule of thumb, around ten samples of each case (train type, direction, track used etc.) are desirable.

For each case an eVDV is calculated using equation {2}, where a(r.m.s.) is either a typical value or, to estimate the worst case situation, the maximum value measured; the numbers of trains in the daytime and night time periods are determined, from the current rail timetable for example; a suitable value of pass-by duration is selected; t = (total number of trains in period x pass-by duration).

The eVDVs for each case cannot be simply added up. Instead, the total eVDV for the period is calculated using the following formula:

$$\text{VDV} = \left(\sum_{c=1}^{c=C} \text{VDV}_c^4 \right)^{0.25} \qquad \text{- \{3\}}$$

where VDVc is the individual VDV for each case, of total number C; ie, raise each individual VDV to the fourth power, sum them, then take the fourth root.

If equipment is used which measures the VDV directly of each train event, then to calculate the total VDV for the period equation {3} is used but with a slight adaptation:

$$\text{VDV} = \left(\sum_{c=1}^{c=C} \left(\text{VDV}_c^4 \times \text{N}_c \right) \right)^{0.25} \qquad \text{- \{4\}}$$

where N_c is the number of trains for each case in the period; ie, raise the representative VDV for each case to the fourth power, multiply each by the respective number of trains in the period, sum them, then take the fourth root.

4.2.2 VDV of Road Traffic Vibration

When the vibration is generally continuous, as for most road traffic induced vibration, the total VDV for the daytime or night time period can be determined by extrapolation from a short-term representative sample VDV. The duration of the sample will depend on the traffic flow rate and composition, but it should encompass a number of pass-bys of each vehicle type using the road.

The VDV for the period is then calculated using one of the following formulae:

$$VDV = 1.4 \times a_1(\text{r.m.s.}) \times (t_p/t_1)^{0.25} \qquad \text{- \{5\}}$$

if the measurements are conducted in terms of weighted acceleration, where a_1(r.m.s.) is the weighted acceleration over the sample period; t_1 is the duration of the sample period (in seconds); t_p is the duration of the period for assessment. Or,

$$VDV = VDV_1 \times (t_p/t_1)^{0.25} \qquad \text{- \{6\}}$$

if the measurements are conducted by measuring a sample vibration dose value (VDV_1 of period t_1) directly.

4.3 Assessment Criteria

To assess the exposure in accordance with the tentative guidance given in BS 6472, the 16 hour daytime and 8 hour night time total VDVs need to be calculated. It suggests that the daytime is 0700 to 2300 and the night time 2300 to 0700. This is consistent with current government planning guidance for noise [4].

For residential buildings, the total period VDVs are compared to Table 7 of BS 6472 to indicate the probability of adverse comments from the occupants:

Vibration dose values ($m/s^{1.75}$) above which various degrees of adverse comment may be expected in residential buildings			
Place	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Residential buildings 16 h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential buildings 8 h night	0.13	0.26	0.51

The Standard distinguishes in the weighting functions between the three axes of vibration. It states that if the orientation of the occupants is varying or unknown with respect to the detected vibration, the weighted values should normally be obtained for all axes and the highest value used. Experience has shown that for road and railway induced vibration the z-axis (vertical) usually produces the highest values.

5. PREDICTION OF VIBRATION LEVELS

5.1 Transfer Functions and Amplification

BS 5228:Part 5 gives guidance on how vibration levels are expected to vary at different locations in a building subject to ground vibration. This guidance was based partly on Wimtec Environmental input to the relevant BSI committee. It states that at point A, on the ground just outside the property, the vibration can be measured as ground vibration. At point B on the solid foundation of the house, the vibration level is lower than at point A because of the loading on the foundations. At point C_1, on the ground floor, the vibration is the same as the foundation vibration for a solid floor, but it can be higher for a timber/joist floor. At point C_2 on a timber/joist upper floor the vibration is higher than the foundation vibration because of the lower mass and stiffness of the floor, allowing higher levels of vibration.

To quantify this, from [5] and the authors' experience, vibration levels from the ground to foundations (A to B) will decrease by up to a factor of two (depending on the measurement conditions at A), and from foundations to first floor (B to C_2) vibration levels will increase by approximately a factor of two to three. Vibration levels across the floors will, however, vary due to modes and depend on the floor construction and area.

5.2 Distance Attenuation

The attenuation of ground vibration with distance is dependant on many factors including soil composition and density, presence of discontinuities such as trenches and foundations, and the effective source input and receiver output positions with the ground. As such it is very difficult to predict without site specific measurement data.

Ideally a survey is conducted at which a representative number of measurements of VDV are taken at different known distances from the source. The results are then plotted and a regression line calculated, assuming that vibration falls off with distance, r, according to a law of the type:

$$\mathrm{VDV} = k\, r^{-x} \qquad \text{- \{7\}}$$

Normally, x is expected to be between 1 and 2.

From the regression the distance from the source at which the category of 'low probability of adverse comment' occurs can be determined, if required.

6. CASE STUDIES

6.1 Example 1

This site was a proposed residential development site, comprising overgrown wasteland at the time of the survey. It was bounded to the north by a slight retained cutting for two railway tracks carrying local services. A tunnel under the centre of the site carried a further single railway track for a local service. All trains were three carriage Electric Multiple Units (EMUs).

Measurements of the train event VDVs were undertaken directly, at a position located above the tunnel. Of the railway to the north the westbound track was approximately 17 m away, the eastbound track approximately 21 m away. The transducers were mounted on a spiked base sited on an existing tarmac access road across the site. The road provided sufficient ground loading to give measured levels indicative of the future foundation levels.

The vibration was greatest in the z-axis. The highest measured values, the numbers of trains in the daytime and night time periods (from the timetable), and the calculated eVDV were as follows:

	Max Event VDV ($m/s^{1.75}$)	Daytime		Night time	
		N° Trains	eVDV ($m/s^{1.75}$)	N° Trains	eVDV ($m/s^{1.75}$)
Eastbound	0.0105	108	0.0338	9	0.0182
Westbound	0.0134	112	0.0436	9	0.0232
Tunnel	0.0424	69	0.1222	4	0.0600

This results in total period vibration dose values of 0.12 $m/s^{1.75}$ and 0.06 $m/s^{1.75}$ for the daytime and night time respectively. Vibration from the trains in the tunnel dominated at this measurement position. Reference to Table 7 of BS 6472 indicates that there is a low probability of adverse comment.

6.2 Example 2

This site was an occupied first floor flat in a low-rise block located adjacent to busy road through a village. The resident had complained that the vibration from the road traffic, especially passing HGVs, caused annoyance. Additional concerns were expressed by the resident of structural damage from the vibration. We were requested by the Local Authority Environmental Health Department to conduct measurements on their behalf.

Measurements of the VDV were undertaken in the resident's flat. The transducers were located on the floor of the front bedroom overlooking the road (the y-axis was parallel to the front wall). A ten minute VDV was measured every hour for three consecutive hours. Ten minutes duration was deemed to include sufficient examples of each vehicle type. The results obtained are given below.

	VDV ($m/s^{1.75}$)		
Sample Time	x-axis	y-axis	z-axis
10:00 – 10:10	0.00700	0.00284	0.00988
11:00 – 11:10	0.00616	0.00247	0.00880
12:00 – 12:10	0.00673	0.00272	0.00964

The vibration was consistently highest in the z-axis; these values were therefore used for the assessment.

The sum of the z-axis $VDV_{10minute}$ values is 0.01247 $m/s^{1.75}$ (effectively a $VDV_{30minute}$ value). Inserting this value as VDV_1 into equation {6} the daytime and night time estimated vibration dose values are 0.030 $m/s^{1.75}$ and 0.025 $m/s^{1.75}$ respectively. This assumes the night time traffic flow is the same as the daytime – a worst case situation.

Reference to Table 7 of BS 6472 indicates that there is a low probability of adverse comment. It is likely that the resident was perceiving low frequency noise from the vehicles as vibration, with rattling windows exacerbating the effect. This is discussed in detail in [5,6].

Measurements of peak particle velocity (ppv) were also undertaken to allow comparison with guide limits for cosmetic and structural damage, of which they were significantly below. When complaints of vibration nuisance are made it is often difficult to ascertain from the complainant whether it is due to actual annoyance or concern of building damage. This must be determined, however, due to the very different methods of assessment.

6.3 Example 3

This site was a greenfield site adjacent to a mainline railway. The most significant vibration was created by freight trains carrying aggregate. Simultaneous measurements were made at two distances from the track – at 27 m and at 37 m. For the seven trains measured, the ratio of VDV values were taken. The mean of the ratios was 1.85. If a relationship of the type given in equation {7} is assumed, then the value of x is 1.34. At this particular site, measurements were made at other distances. The highest VDV was measured at 5 m from the track and was 1.5 $m/s^{1.75}$ for the night time. To determine the distance at which the VDV is at a level where there is a low probability of adverse comment, ie a VDV of 1.3 $m/s^{1.75}$, equation {7} can be rearranged thus:

$$\left(\frac{VDV_1}{VDV_2}\right)^{1/x} = \frac{d_2}{d_1} \qquad \text{- \{8\}}$$

Where VDV_1 is the vibration dose value at distance d_1 etc, and d_2 is greater than d_1. For the values given above, the distance at which the VDV is 1.3 $mm/s^{1.75}$ is:

$$5\times\left(\frac{1.5}{1.3}\right)^{1/1.34} = 6\,\text{m}$$

7. REFERENCES

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