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ASSESSING THE EFFECT OF ENVIRONMENTAL VIBRATION IN BUILDINGS BS 7385 : PART 2

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1. INTRODUCTION

Groundborne vibration from environmental sources such as blasting, piling and other construction activities, machinery and road/rail traffic has always been a source of concern to nearby residents. Work began on BS 7385 : Part 2, "Measurement and Evaluation of Vibration in Buildings, Part 2, Guide to Damage Levels From Groundborne Vibration" in 1986, when there were in existence documents which dealt with the human response to vibration in buildings, but no BS document dealing with the effects of vibration on buildings and their components. There was however, a Draft International Standard, ISO DIS 4866 (which was formally issued in 1990 and dual numbered as BS 7385 Part 1 : 1990 [1]) which set out the methods of measuring and evaluating vibration in buildings. It was intended that DIS 4866 would serve as a base document for BS 7385 : Part 2. It was considered in 1986 that the time was ripe for a UK document which addressed the requirements of UK industry and society.

The work to prepare a new BS standard was planned in two stages. Stage 1 was the collation, expansion and evaluation of the UK database, with the intention of using it as the foundation for a Draft BS, in the light of international data and experience. The preparation of the Draft BS was conceived as Stage 2 of the work.

The case history study was carried out over the period 1986 - 1988 and the overall findings are discussed in this paper. The new Standard [2] has gone through 7 stages of drafting, having passed the public comment stage earlier this year and will shortly be published by BSI. The development and organisation of the Standard are discussed in detail in a later section of this paper.

Details of the recommended measurement procedure and the proposed method of assessment of vibration magnitudes against vibration guide values will be clarified. Finally, cases which may require special consideration are identified.

2 VIBRATION-INDUCED DAMAGE

2.1 Origin of Vibration-Induced Damage

Vibration-induced damage can arise in different ways, making it difficult to arrive at universal criteria which will adequately and simply indicate damage risk. Three mechanisms are usually identified:

(a) **Direct vibration damage** - high dynamic stresses are induced which exceed the material limit in previously undamaged construction not exposed to pre-existing abnormal stress.

(b) **Accelerated ageing** - lower levels of induced dynamic stress accelerate normally occurring damage arising from say, foundation settlement.

(c) **Indirect vibration damage** occurs when high quasi-static stresses are induced by, for example, soil compaction.

Since the new Standard considers only the direct effect of vibration on a building, it is important to distinguish between these different categories when using the proposed criteria. It has been recently suggested by representatives from France and Germany to ISO committee ISO/TC108/SC2/WG3, dealing with "Vibration of Stationary Structures", that the relevant national standards in these countries may include consideration of indirect vibration effects. This may partly account for significant differences between guide values recommended in the new BS and in the other national codes.

2.2 Description of Damage

For the purposes of BS 7385, damage is classified into the following categories [1]:

* **Cosmetic.** The formation of hairline cracks on drywall surfaces or the growth of existing cracks in plaster or drywall surfaces; in addition, the formation of hairline cracks in mortar joints of brick/concrete block construction.

* **Minor.** The formation of large cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.

* **Major.** Damage to structural elements of the building, cracks in support columns, loosening of joint, splaying of masonry cracks, etc.

Guide values given in the new BS are associated with the first category - the onset or threshold of cosmetic damage.

ASSESSING VIBRATION IN BUILDINGS - BS 7385 : PART 2

2.3 Cracking in Buildings

All buildings crack, immediately after construction or over a period of years, dependent on the methods and materials used in construction and the change in the support conditions. The period of time before natural deterioration occurs depends upon the stresses imposed over the life of the building, as well as the resistance of the materials to physical and chemical effects.

There are many causes of movement in a building such as heat, moisture, settlement, occupational loads, pre-stressing forces, material creep and chemical changes. An optimised design should normally permit adequate relaxation of stress concentrations by movement joints, or by providing further support or reinforcement. The time rate of cracking due to natural ageing may be increased by an external disturbance. Any change in cracking rate will only be detected by careful inspection before and after each external disturbance, i.e., the imposed environmental vibration. There will also be a small increase in cracks or crack length due to day/night expansion and contraction and seasonal variations. Pre - and post exposure crack inspections should therefore be carried out at the same time of the day, and should be such that seasonal effects are avoided if possible.

Wall and/or ceiling lining materials are usually the most sensitive to vibration imposed on buildings; and should be examined first for any evidence of cosmetic cracking. Age and the existing condition of the building are factors to consider when assessing what natural cracking may have occurred, together with evidence of any alterations. These may have been built to a different standard, with a deeper foundation for example. Concern over the existing cracking depends upon whether they are surface or through-cracks, whether they are likely to open further or close, whether they are repairable or capable of being covered by decoration, and whether water penetration is a factor.

2.4 Causes of Building Damage other than Vibration

The various causes of damage to buildings which are summarised in Table 1. Settlement, temperature changes and shrinkage effects are, among others, common reasons why damage is observed in buildings. The problem is that damage due to these mechanisms may go unnoticed for some time, but becomes attributed to environmental vibration which is as an unwanted intrusion into the house owner's privacy. If the vibration magnitude is above the threshold of annoyance to people, a house owner becomes naturally concerned about possible damage to his property. He begins to look for cracks, which, if present, may have been developing for some time due to these other causes and assumes that they must be due to the imposed vibration. For this reason, pre- and post-exposure surveys are essential to avoid drawing inaccurate conclusions.

The magnitude of wall displacements due to blasting are compared with those due to environmental effects in Figure 1. It is clear that expansions and contractions due to temperature changes are generally greater than wall strains due to blasting [3].

3. CASE HISTORY STUDY IN UK

3.1 Background to Study

Two methods of obtaining useful data are possible: carrying out an in-depth systematic study on one or perhaps several buildings or assembling together case history data from a much larger number and different types of buildings. The advantage of the first approach is that the various factors which could potentially influence the response of a building to an external source of vibration may be independently controlled, but the application of the results may be restricted to similar buildings. The case history approach has the limitation that the data is variable in nature and quality. An attempt was made by the BSI to gather together data which was already available in reports, relying on the co-operation of organisations holding such information as part of their normal responsibilities..

3.1.1 Data Collection Approaches to organisations for data on the effects of vibration on buildings, with particular reference to damage. were made on behalf of the BSI, Detailed information on individual case histories was requested through a questionnaire in the form of Figure 2, which identified the vibration source, the measured value (including position, frequency and magnitude), the building type and any comments regarding damage, where applicable. It was pointed out in the request that since the majority of cases do not involve building damage (the sparsity of actual damage data became apparent very early on), data was also being gathered for cases where no damage was caused, but where building vibration levels were greater than 2 mm/sec ppv. This qualification of the survey question was found necessary at the data gathering stage, but introduced bias in the dataset which had to borne in mind at the later analysis stage.

453 organisations were contacted with the breakdown shown in Table 2 In all, 630 cases were assembled from data supplied from 37 organisations. Although some organisations and individuals contributed a great deal in supplying data and assisting in tracing references for a parallel literature review, it was disappointing that so many were not in a position to provide any contribution at all. The response from public organisations was in general better than from commercial companies, as could be expected. Commercial companies were concerned that they could not justify the time required to search through their files to find the data without some reimbursement, although they supported the study and wished to be associated with it. There was also in some cases a natural reluctance in allowing an party access to their files to save them having to extract the data themselves.

TABLE 2 ORGANISATIONS CONTACTED FOR RELEVANT DATA

Type of organisation	No. Approached
Specialist consultants	27
Civil & Structural Consulting Engineers	69
Building and Foundation Contractors	20
Explosives Engineers	6
Mine and Quarry operators	44
Industrial Organisations	64
Trade Associations	9
Professional Bodies	10
Local Authorities	109
Insurance Companies	52
Research Establishments	11
Universities and Colleges	32
Total number of organisations	453

Certain data was the subject of current litigation and there was also a reluctance to release data without a meeting to allay fears that sensitive or confidential information was to be published in an unacceptable form. One potential source of a large quantity of data relating to blasting vibration did not release data because the organisation had at that time a policy decision (for good reason) not to release publicly the results of their environmental monitoring programmes. This policy has now been changed and more data has recently become available.

3.1.2 Data Quality The data collected was found to be of variable quality and completeness, which might be expected from information originally recorded for a variety of reasons and using different procedures. Vibration magnitude, direction and measuring position were all recorded, but less consistent was the recording of frequency content, source type and building/ground conditions. Discrepancies were noticed in the method of determining the resultant, where often the simpler, but incorrect method of taking the square root of the squares of the maximum levels of the three components was calculated. The introduction of BS 7385: Part 2, which recommends the correct way of obtaining the true resultant from simultaneous recording of the three time histories, should improve the quality of data collected in the future.

The survey of measured data, will tend to represent the range of vibration between that causing concern (whether from personal annoyance or fear of damage to the building), and that which is the highest normally encountered. If an analysis of all vibration imposed on buildings were required, then a survey would have to be carried out on a statistically representative sample without any bias towards those causing concern. Political sensitivity of a particular type of vibration source can lead to a disproportionately large number of measurements of that source. The dataset becomes filtered not only in terms of vibration level, but also in terms of source type and building type. High vibration levels will generally cause less concern and will generally be measured less often in an engineered building structure, than in a domestic property. What may be said is that the available data represents those levels causing more than human annoyance, and as such is relevant to the information required when considering damage.

3.2 Evaluation of UK Database

3.2.1 Data Presentation The data was presented with the source first described, followed by the building, including foundation and soil type. Sources were classified according to the characteristics of the vibration produced. Blasting and piling were the most common sources of vibration to be measured, as shown in Figure 3.

The measured vibration was in general taken at the foundation of the building, or close to the ground at an outside wall, representing the vibration input to the building. Magnitudes in other parts of the building will be determined by the response to that input, and may well be higher than the input level. The use of a damage criterion based on measurement at a single point on the building is subject therefore to a degree of uncertainty. This is mitigated somewhat, by the fact that the response to particular types of vibration of a sample of buildings of similar construction is likely to be representative of that construction type.

Buildings were classified in accordance with what was then ISO/DIS 4866 (now ISO 4866 : 1990 or BS 7385; Part 1 : 1990 [1]). Two storey domestic buildings were the most prevalent type to be measured, as indicated in Figure 4.

Comments on any damage observed were recorded according to the three categories already discussed. In most cases structural surveys were not carried out before the vibration occurred. Where damage was claimed, it was often difficult, to substantiate the cause as vibration. Pre-exposure structural surveys are rarely carried out, because of the cost involved and the fear of arousing public suspicion and anxiety. Damage which is first noticed following the exposure was not always thoroughly investigated. It is sometimes cheaper, and more acceptable from a public relations point of view, for a company to settle small damage claims rather than question their validity.

3.2.2 Data Analysis Discriminant analysis was initially considered as a method of separating the data into "damage" and "no damage" categories, based on the combination of a number of variables. The variables would be all the parameters influencing whether damage was caused, including the vibration magnitude, frequency and characteristics, the susceptibility of the building to damage (i.e., structural type, state of repair, frequencies, soil type, foundation type, etc). In order to use this analysis method, all these variables would have to be quantified numerically. The numbers thus produced would also have to follow a normal distribution for each variable. The lack of completeness in the measurement records however, and the qualitative nature of many of these parameters, precluded such an approach.

The data was therefore analysed initially according to a series of graphical distributions for each source type, each building type, and by vibration magnitude band as shown, for example, in Figure 5. The distribution of magnitudes of the complete set of data did not follow a normal distribution, but was skewed. Also shown on this Figure are the number of damage cases in each magnitude band.

3.2.3 Data Evaluation It was disappointing that there were only 30 cases where damage originally attributed to vibration had occurred, and that these were spread over a fairly wide range of vibration magnitudes, extending from as low as 1 mm/sec ppv. There was however, a general lack of formal pre- and post-exposure structural surveys the damage data cannot be accepted at face value.

Vibration magnitudes and probable causes of damage for each of the 16 damage cases in the general subset of the data are given in Table 3. The other 14 damage cases were all obtained from one organisation and not amenable to objective independent verification.

Careful scrutiny of the 16 reported damage cases revealed many to be suspect, with good grounds for supposing the cause to be other than vibration. There is a tendency for reported cases of vibration-induced damage to acquire authenticity through initial uncritical acceptance and subsequent inclusion in more authoritative review documents. In the case of this dataset, close investigation shows only 5 of the 16 claimed cases of damage were likely to be directly induced by vibration, with some uncertainty still remaining for several of these. A recurring problem data which was originally obtained to solve a complaint at the time, is that accompanying notes are often anecdotal in nature, making an independent check impossible..

ASSESSING VIBRATION IN BUILDINGS - BS 7385 : PART 2

TABLE 3 DETAILS OF DAMAGE CASES

Case No.	Peak Component Particle Velocity mm/sec	Comment on result/ Probable cause of damage
1.1.41	47.2	Vib (opencast blasting)
1.1.42	36.4	Vib (quarry blasting)
2.4.21	14	possibly due to vibration
2.4.25	25.4	Possibly due to vibration
2.6.26	21.3	Possibly due to vibration
2.3.8	2.6	Previously cracked mortar cornice
2.3.9	1.2	Seriously defective ceiling, already cracked, no longer properly keyed to laths
2.4.24	7.4	No independent verification
2.4.58	6.4	Differential settlement
2.6.4	3.1	Shrinkage
2.6.5	3	Alleged but not verified
2.6.7	1	Alleged but not verified
2.7.23	1.4	Backfilled ground of variable density
2.8.9	2.8	Alleged but not verified
2.8.10	8.1	Alleged but not verified
6.1.2	4	Displacement measured ppv calculation dubious

The problem of positively identifying the cause of damage is also compounded by the fact that vibration and settlement can be interlinked. Vibration can cause compaction of loose soils, so that settlement damage may in certain cases be an indirect result of vibration. The large proportion of buildings in the survey claimed to be damaged by vibration were in fact built on poor ground. This distinction between direct and indirect vibration damage was considered necessary by the BSI Committee, because the mechanisms are different, requiring differentiation between causes. It is for this reason that only the direct effect of vibration on buildings is considered in BS 7385 : Part 2 : 1993.

Figure 6 has been prepared to give an indication of the proportion of cases exhibiting damage relative to the total number of cases recorded in each ppv band. The graph would suggest that there is greater risk of damage occurring above say 15 mm/sec ppv. However, percentage values on the ordinate scale may be misleading for two important reasons. Firstly, the assumption of an unselective mechanism for gathering data does not apply - the dataset has an in-built deliberate bias arising from the questionnaire. Secondly, there is a sparsity of data above 15 mm/sec ppv (only 10 damage cases), which is not readily apparent when a ratio is taken. As a consequence, this result was initially regarded as an interesting trend only.

3.3 Literature Review

A review of relevant literature was carried out to provide a background of UK and international experience in the following subject areas:

* Building damage vibration limits
* Building damage and vibration in general
* Vibration from construction operations (including piling)
* Vibration from blasting (construction, quarry, opencast coal mining)
* Vibration from underground blasting
* Vibration from explosive demolition
* Dynamic stresses associated with building vibration
* Vibration from road traffic
* Vibration from rail traffic
* Building damage due to quasi-static effects

It was not within the scope of the study to carry out a critical review of the published literature, but rather give a representative background against which the UK data could be evaluated. The peak particle velocity has been used as the criterion for assessing the risk of vibration-induced damage in BS 7385 : Part 2, because it has not been displaced as the commonest simple indicator, probably because it has a reasonable theoretical basis [4,5] and is simple to use. The comparison of various national standards (which have various qualifications in the assessment) indicated that ppv guide values range from 5 to 19 mm/sec over the frequency range 4 - 15 Hz, 6 to 50 mm/sec over 15 - 40 Hz and 10 to 50 mm/sec over 40 - 100 Hz. The divergence of opinion was most marked above 40 Hz, with limits proposed in the USA, Sweden and UK (for specifically highway excavation blasting) being 2.5 times higher than French, Swiss, German or other UK (opencast coal mining) limits. Early research of a systematic nature [6,7,8] indicated a ppv limit for avoiding vibration-induced damage in the range of 50 - 75 mm/sec (2 - 3 in/sec, in fact). If the "method of halves" applied twice to improve the factor of safety to the lower end of this range results in 12.5 mm/sec, which is the UK opencast blasting vibration limit! Although the US Bureau of Mines [9] now recommend this value as the 95% confidence limit, when frequency is not taken into account, the alternative frequency-dependent criteria range up to 50 mm/sec above 40 Hz.

unsatisfactory situation, when it appears that the supporting databases for such limits appear to be no better than our own.

4.2 Planning of BS 7385 : Part 2

The immediate tasks involved in drafting the new Standard were to review literature published since Stage 1, examine any new damage data, review new relevant codes, examine in more detail the systematic field data available elsewhere, and review the elicitation of expert opinion on threshold values obtained by ISO TC108. Whereas BS 7385 : Part 1 deals with the measurement of vibration in buildings, the emphasis in Part 2 was to make quantitative recommendations on the assessment. A further aspect of the work was to consider those factors of particular concern for railway sources, i.e., intermittency and the common requirement to measure at the highest floor level in a building.

4.3 Scope of Standard

It is intended that the Standard will deal with ground vibration from sources such as blasting, piling, machinery or road/rail traffic. Guide values for building vibration based on the lowest vibration levels above which damage has been credibly demonstrated. The Standard covers the characteristics of building vibration, factors which influence response, measurement procedures, and assessment of measured vibration against guide values.

Excluded are the movement of loose objects within or on buildings, sensitive equipment or human tolerance. The levels of vibration at which adverse comment from people is likely are below levels of vibration which damage buildings, except at lower frequencies. Also excluded are the effects of earthquakes, air overpressure, wind or sea actions. Since the recommended measurement location is at the entry point to the building, the standard applies to vibration transmitted through the ground from outside the building and not to internal sources. Special structures such as tunnels, pipelines, chimneys and bridges are not covered.

4.4 Characteristics of Building Vibration

The Standard considers vibration to be characterised in terms of type of source, the duration and the frequency range of the input. Duration effects dynamic magnification, particularly for continuous vibration, if the natural frequency of the structure is close to the forcing frequency. BS 7385 : Part 1 recommends that if the forcing function acts on the structure continuously for less than 5 times the time constant, then the building response should be regarded as transient. Further consideration of this aspect is now seen to be required, following consideration of railway vibration, and will be addressed when Part 1 is reviewed. The limit above which damage may be caused for vibration of a continuous nature may need to be lower than the corresponding limit for transient vibration.

The lowest frequency covered by Part 2 of BS 7385 is 1 Hz and the highest frequency expected from close-in construction blasting in hard ground is 1000 Hz. A more limited range of 1 - 250

Hz is defined in the guide values, although definitive data is not available above 100 Hz. When selecting guide values, it is the frequency of the input vibration to the building which is of relevance.

4.5 Factors Effecting Building Response
The response of a building is effected by the type of foundation and soil conditions, the type and construction of the building and in particular the building components. BS 7385 : Part 2 recommends consideration therefore of each of these factors.

4.5.1 Foundation Type and Ground Conditions The degree of fixity provided by the building foundation in the ground, has a major effect on building response; and the geology of the ground between the vibration source and the building affects the input frequency spectrum to the building. In general stiffer foundations result in higher natural frequencies of the building-soil system and higher input frequencies are often associated with harder ground. A higher p.p.v. measured with harder ground may also induce the same strain as a lower p.p.v. measured with softer ground. However,since the measurement procedure gives the input vibration to the building, the assessment according to this Standard, only recommends different guide values for different types of building.

4.5.2 Type and Construction of the Building Primarily, the building response to a given input vibration depends upon the natural frequencies, mode shapes and damping. Higher levels of strain will result when dominant frequencies in the excitation spectrum are close to natural frequencies. Older, low-rise masonry structures tend to have higher natural frequencies in comparison with modem lightweight, flexible and taller buildings. Also the natural frequencies of building components such as walls, floors and ceilings, are usually higher than the frequencies of whole-body modes of the building, and are more susceptible to excitation at resonance by continuously operating machinery, than the building as a whole. Different guide values appear in the Standard according to building type.

4.6 Measurement of Vibration
The standard defines what should be measured, where to measure and a procedure for acquiring data in a manner which ensures that all the relevant data is obtained.

4.6.1 Quantity to be Measured Peak particle velocity has been used for the reasons given in 3.3, and also because it is the best single descriptor for correlating with case history data on the occurrence of vibration-induced damage. BS 7385 : Part 2 recommends the simultaneous recording of unfiltered time histories of the three orthogonal components of particle velocity, which allows any desired value to be extracted at a later stage. The maximum of the three orthogonal components is used for the assessment, because the majority of data on which guide values have been based are expressed in peak component particle velocity. In order to provide data for possible future revision, it has been recommended that the peak true resultant particle velocity, obtained by vectorially summing the three orthogonal components coincident in time, should be derived. Further use of the maximum vector sum, which takes the maximum of each component regardless of the time when it occurs, is discouraged in this new Standard, because it may include a large unknown safety factor.

4.6.2 Measuring Positions The measuring position recommended is at the base of the building, on the side of the building (or, if not possible, on the ground outside), facing the source of vibration. Other positions should be taken for the purposes of a more detailed engineering analysis (as defined in 9.2.4 of BS 7385 : Part 1 : 1990).

This goes some way to offset the dilemma faced by those dealing with multi-storey buildings, where a measurement at foundation level will not usually be indicative of the maximum vibration level likely to occur within a building. If guide values were defined at the top of a building, then it would not be necessary to define the amplifications that may occur. Taking average amplifications can overestimate or underestimate the maximum value, and the amplification can of course vary with both direction and frequency.

Since existing data does not permit definition of top floor guide values, an alternative evaluation technique has been introduced in the Standard. The response spectrum approach will give more precisely the maximum amplification due to a particular event. This approach could usefully be tested in the future for both railway vibration and multiple-delay blasting, which can have a duration of greater than 5 times the time constant.

4.6.3 Instrumentation and Measurement Procedures Brief guidance is given on mounting of the transducer and the instrumentation appropriate to the type of investigation being undertaken i.e., a preliminary assessment, a monitoring program, a field survey or a detailed engineering analysis. As with many other aspects of the measurement process, reference is made to Part 1 of BS 7385. The survey record should be consistent with the type of investigation required, but should include information on the vibration source, the site layout, ground conditions, type of building and condition, instrumentation and results [13].

One of the particular features of the Standard is that quite detailed guidance is given in an appendix on the data which may be relevant to record during a field survey. The intention is not to be overly prescriptive, but rather to ensure that sufficient details are recorded to define the case. One of the main problems encountered during the UK data survey was the incompleteness of the case details. The listing also serves as a prompt, for the investigator to check that no relevant fact is overlooked, and to permit an objective "before and after exposure" comparison for assessing any complaints which may arise.

4.7 Assessment of Vibration

Assessment of the risk of vibration-induced damage according to BS 7385 : Part 2 takes into account the magnitude, frequency and duration of recorded vibration together with consideration of the type of building which is exposed.

4.7.1 Basis for Damage Criteria As discussed earlier, Case-history data, taken alone, has so far not provided an adequate basis for identifying thresholds for vibration-induced damage. Data from systematic studies [6 - 9,11,12,14 and 15], using a carefully controlled vibration source in the vicinity of buildings has therefore been used as the basis for defining damage thresholds. The vibration levels suggested are judged to give a minimal risk of vibration induced damage. Data from the US Bureau of Mines (Siskind et al [9]), which is a substantial and credible review of data at high magnitudes, suggests that the probability of damage tends towards zero at 12.5 mm/sec peak component particle velocity, as shown in Figure 7. This USBM dataset includes data from USA, Sweden, Canada and Britain for mainly blasting vibration and is notable in that it is all analysed statistically. The result of this analysis is not inconsistent with an extensive review of the case history information available in the UK, as indicated in Figure 8, where the data from the cumulative distribution of Figure 6 is overlaid on the USBM dataset.

4.7.2 Assessment of Vibration Frequency A frequency-based vibration criterion is given in the Standard because the relative displacements associated with cracking will be reached at higher vibration magnitudes with higher frequency vibration [3]. Some estimation of the frequency content of the recorded vibration must therefore be made. The dominant frequency to use for the assessment is that associated with the greatest amplitude pulse. The method of estimating frequency depends on whether the vibration time history is simple or complex in character. The simplest case consists of a time history record with a single dominant pulse, where the dominant frequency may be taken as the inverse of twice the time interval of the two zero crossings on either side of the peak. This technique is only reliable where the vibration consists of a single frequency [17]. In more critical circumstances or if a visual examination of the vibration time history shows that it is multi-frequency in nature, then frequencies should be determined from an amplitude-frequency plot, with each significant peak being examined in turn [18]. This approach may not always be straightforward with complex time histories and care is needed in interpretation, but as yet, no simple and reliable alternative has been identified.

4.7.3 Transient Vibration Guide Values Limits for primarily transient vibration, above which cosmetic damage could occur are given numerically in Table 4 and graphically in Figure 9. In the lower frequency region where strains associated with a given vibration velocity magnitude are higher, the guide values for the building types corresponding to line 2 are reduced. Below a frequency of 4 Hz, where a high displacement is associated with a relatively low peak component particle velocity value a maximum displacement of 0.6 mm (zero to peak) is recommended.

4.7.4 Continuous Vibration Guide Values The Standard proposes a 50% reduction in guide values to allow for dynamic magnification due to resonance, where this occurs, as with continuous vibration. This recommendation is not supported by damage data, but is based on common practice [19].

4.8 Special Cases

This section deals with other factors which may be relevant to the assessment, such as fatigue, indirect damage, and importance of the building.

4.8.1 Fatigue There is little probability, and a lack of verifiable evidence for fatigue damage occurring in residential building structures due to either blasting [3,20], normal construction activities or vibration generated by either road or rail traffic. The increase of the component stress levels due to imposed vibration is relatively nominal and the number of cycles applied at a repeated high level of vibration is relatively low.

4.8.2 Building Importance, Age and Condition Important buildings which are difficult to repair may require special consideration on a case-by-case basis. A building of historical value should not (unless it is structurally unsound) be assumed to be more sensitive.

The age and existing condition of a building are also factors to consider in assessing the tolerance to vibration. Older buildings may have soft mortar joints, simple footings or poor cross-bracing. Previous damage due to sources other than vibration may also be masked by recent renovation and redecoration. The existence of a major alteration can be a specific cause of increased rate of cracking. If a building is in a very unstable state, then it will tend to be more vulnerable to the possibility of damage arising from vibration or any other disturbance. Again, however, no automatic reduction in the guide values is recommended in the Standard, each case must be considered individually.

4.8.3 Building Damage Due to Soil Compaction Damage to buildings can sometimes arise indirectly from vibration in certain ground conditions. Depending upon the type of ground, ground vibration can cause consolidation or densification of the soil [3,21], which has been known to result in differential settlement and consequent building damage. Loose and especially water saturated cohesionless soils are vulnerable to vibration which may cause liquefaction. There are cases where the acceptable vibration limit may be set by considerations of soil-structure interaction, rather than distortion or inertial response of the building itself. The Standard gives brief guidance on the possible need to consider a lower limit forthis situation.

5 CONCLUSION

A new British Standard on the effect of groundborne vibration on buildings has been developed. Guide values for environmental vibration are given for both transient and continuous vibration at the foundation level of the building. These guide values have been proposed based upon a survey of damage data of UK origin, and a review of both international data and experience.

Procedures for both vibration measurement and pre/post exposure building inspections are recommended to ensure that as far as possible, effects are attributed to the correct cause.

There remain areas for development in the future, associated with evaluation at building locations away from the foundation level particularly maximum dynamic magnification, and the correct assessment of frequencies in complex waveforms. Further systematic studies are also called for on UK type building constructions, indirect building damage including liquefaction and accelerated ageing at low vibration levels.

6. REFERENCES

[1] BS 7385 : Part 1 : 1990, Evaluation and measurement of vibration in buildings, Part 1., Guide for measurement of vibrations and evaluation of their effects on buildings.

[2] BS 7385 : Part 2 : 1993 (Final Draft for BSI Editor), Measurement and evaluation of vibration in buildings, Part 2., Guide to damage levels from groundborne vibration.

[3] DOWDING, C.H., Blast vibration monitoring and control, Prentice-Hall, NJ, USA, 297 p, 1986.

[4] NEW, B.M., Ground vibration caused by civil engineering works, Transport and Road Research Laboratory Research Report 53, 1986, Available from Transport Research Laboratory, Crowthorne, Berkshire, RG11 6AU.

[5] GASCH, R., and KLIPPEL, P., Estimation of the dynamic stressing of floors and other structural parts of buildings due to shocks and blasting - determination of stresses by measurement of vibration velocity, Vibrations of Concrete Structures, Sp-60, American Concrete Institute, 1979.

[6] EDWARDS, A.T., and NORTHWOOD, T.D., Experimental studies of the effects of blasting on structures, The Engineer, Sept. 1960, pp 538-546.

[7] NORTHWOOD, T.D., CRAWFORD, R. and EDWARDS, A.T., Blasting vibrations and building damage, The Engineer, May 1963, pp 973-978.

[8] NICHOLLS, H.R., JOHNSON, F.J. and DUVALL, W.L., Blasting vibrations and their effects on structures, United State Bureau of Mines Bulletin 656, 1971.

[9] SISKIND, D.E., STAGG, M.S., KOPP, J.W. and DOWDING C.H., Structure response and damage produced by ground vibration from surface mine blasting, United States Bureau of Mines, Report of Investigations No. RI. 8507, 1980.

[10] STUDER, J. and SUESSTRUNK, A., Swiss standard for vibrational damage to buildings, comments on SN 640 312, "Effects of vibrations on structures', 1978.

[11] HOOD, R.A. and MARSHALL, C.P., The effects of simulated traffic vibration on a dwelling house, Transport and Road Research Laboratory Research Report No. CR 44, 1987, Transport Research Laboratory, Crowthorne, Berkshire, RG11 6AU.

[12] White, T.J., Farnfield, R.A., and Kelly, M., The effect of surface mine blasting on buildings, Proc., Fourth International Symposium on Rock Fragmentation by Blasting, Int. Soc. of Rock Mech., Vienna, July 1993.

[13] BRE Digest 353, Damage to structures from ground borne vibration, 1990, Available from the Building Research Establishment, Watford, Herts, WD2 7RJ.

[14] WISS, J.F. and NICHOLLS, H.R., A study of damage to a residential structure from blast vibrations, The Research Council for the Performance of Structures, American Society of Civil Engineers, 1974.

[15] LANGEFORS, U and KIHLSTROM, B., The modern technique of rock blasting, 3rd edn 1978, (New York:Wiley, Halsted Press), 438 p.

[16] WISS, J.F., Construction Vibrations: state of the art, American Society of Civil Engineers, Journal of the Geotech. Eng. Div., Feb., 1981, pp 167 - 181.

[17] CRENWELGE, O.E., Transient data analysis procedure for reducing blast-induced ground and house vibrations, Proc., 17th Conf. Explosive and Blasting Technology, 1991, Las Vegas.

[18] DOWDING. C.H., Coordinator for the Working Group of the Conmission on Testing Methods, Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr. Vol 29, No. 2. pp. 143-156, 1992, Suggested method for blast vibration monitoring.

[19] BS 5228, Noise Control on Construction and open sites, Part 4 : 1992, Code of Practice for Noise and Vibration Control Applicable to Piling Operations.

[20] MEDEARIS, K., Rational damage criteria for low-rise structures subjected to blasting vibrations, Pro. Inst. Civ. Engrs., Part 2. 1978, 65, Sept., pp 611-621.

[21] COMMITTEE OF EARTHQUAKE ENGINEERING, National Research Council, Liquefaction of soils during earthquakes, National Academy Press, Washington DC, 1985.

TABLE 1 CAUSES OF BUILDING DAMAGE OTHER THAN VIBRATION

Vibration is often wrongly blamed for the damage observed in building. There are many other causes, a selection of which is given below.

	CAUSE	EFFECT	DURATION
1	Temperature changes	Expansion, contraction	Seasonal
2	Drying	Shrinkage	Short-term
3	Soil movement eg. subsidence, creep	Settlement	Intermittent
4	Loading of ground	Settlement	Intermittent
5	Structural overloading eg. loss of support	Excessive deflection, distortion	Intermittent
6	Sulphate attack	Expansion	Continuous
7	Carbonation of cement products	Shrinkage	Continuous
8	Corrosion of metals	Expansion	Continuous
9	Loss of volatiles in mastic compounds	Contraction	Short and long-term
10	Ice formation	Expansion frost heave	Intermittent

Extracted from BRE Digest No.75 'Cracking in buildings' 1966 (rep 1975) (Superseded now by BRE Digest 361 'Why do buildings crack', 1991)

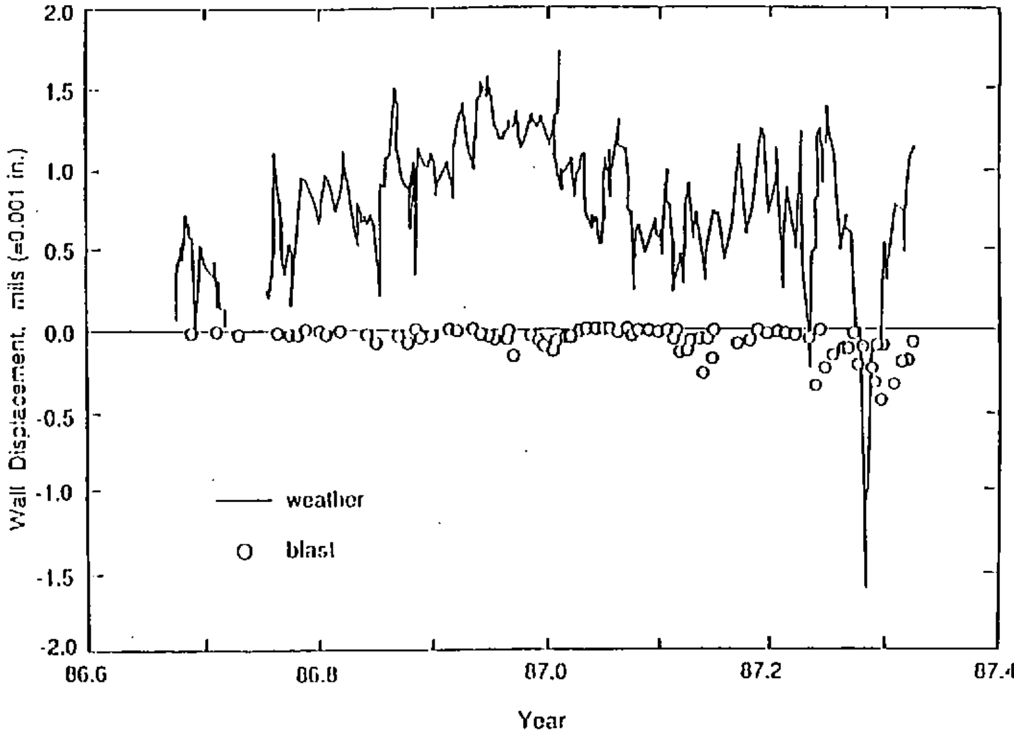

FIGURE 1 COMPARISON OF ENVIRONMENTAL WALL DISPLACEMENTS WITH THOSE DUE TO BLASTING

Case reference	Source classification: Description	Building classification: Type	Foundation	Soil	Distance / m	Description
2.1.1	Tripod bored piling	8	-	-	20	End of terrace house, in poor state with shored walls
2.1.2	Tripod bored piling, 450mm diameter piles at depths up to 18m	6	-	-	-	Public house in indifferent condition
2.1.3	Tripod bored piling	5	-	-	5	Substantial brick 2 storey house
2.1.4	Tripod bored piling	4	B	-	5	2 storey brick clad hospital
2.1.5	Tripod bored piling	2	-	-	4	Post Office sorting hall
2.1.6	Tripod bored piling	4	-	-	3	6 storey building with retained facades
2.1.7	Tripod bored piling	2	B	-	4	Computer room in modern multi storey offices
2.1.8	Tripod bored piling	2	-	-	1	Edwardian steel framed brick clad building
2.1.9	Tripod bored piling	5	-	-	1	4 storey, 100 year old masonry office building
2.1.10	Tripod bored piling	6	-	-	-	Residential housing

Key to building classification (accords with ISO/DIS 4866)

Type:
1 - Heavy industrial
2 - Large reinforced concrete, and steel framed
3 - Light industrial, and timber framed
4 - Heavy domestic
5 - Medium domestic
6 - Two-storey domestic
7 - Light domestic, and stone churches
8 - Fragile listed buildings

Soil:
a - Solid rock
b - Compact, horizontally bedded
c - Poorly compacted, horizontally bedded
d - Sloping surfaces (potential slippage)
e - Sand, gravel, or clay
f - Fill

Distance: Horizontal distance between source and nearest facade of building

Foundation:
A - Linked concrete piles, reinforced concrete raft, linked timber piles, or heavy retaining walls
B - Non tied piles, spread wall footing, or wooden raft
C - Light retaining walls, stone footing, or direct onto soil

Measured vibration: Direction	Frequency Hz	Magnitude mm/s p.p.v	Comments	Observed damage: Pre-exposure	Post-exposure	Cause	Description
V	-	1	Measured on end wall	2	2	-	No worsening of existing condition
R	18 to 45	8.15	Peak when boring through timber and brick obstructions. Measured on wall at ground level	3	3	-	No worsening of existing condition
R	-	2	Measured on wall at ground level	4	4	-	-
R	-	3	Measured on wall at ground level	4	4	-	-
R	-	12	Measured on wall at ground level	4	4	-	-
R	-	8	Measured on wall at ground level	4	4	-	-
R	-	2.5	Measured on computer room floor (4th)	4	4	-	-
R	-	12.7	Measured at wall at ground level	4	4	-	-
V	-	6	Measured at wall at ground level	4	2	b	Major cracking due to settlement
V	-	2	Measured at wall at ground level	3	3	-	Facades in poor condition, treated with cladding

Key to measured vibration

Direction: V - Vertical H - Horizontal R - Resultant

Frequency: Predominant frequencies or frequency range

Magnitude: Peak particle velocities

Key to damage

Extent, pre- and post-exposure:
1 - Major structural damage
2 - Minor structural damage
3 - Architectural damage
4 - No significant damage

Cause (of change):
a - Vibration
b - Settlement
c - Air over-pressure
d - Other

FIGURE 2 FORMAT FOR DATA COLLECTION

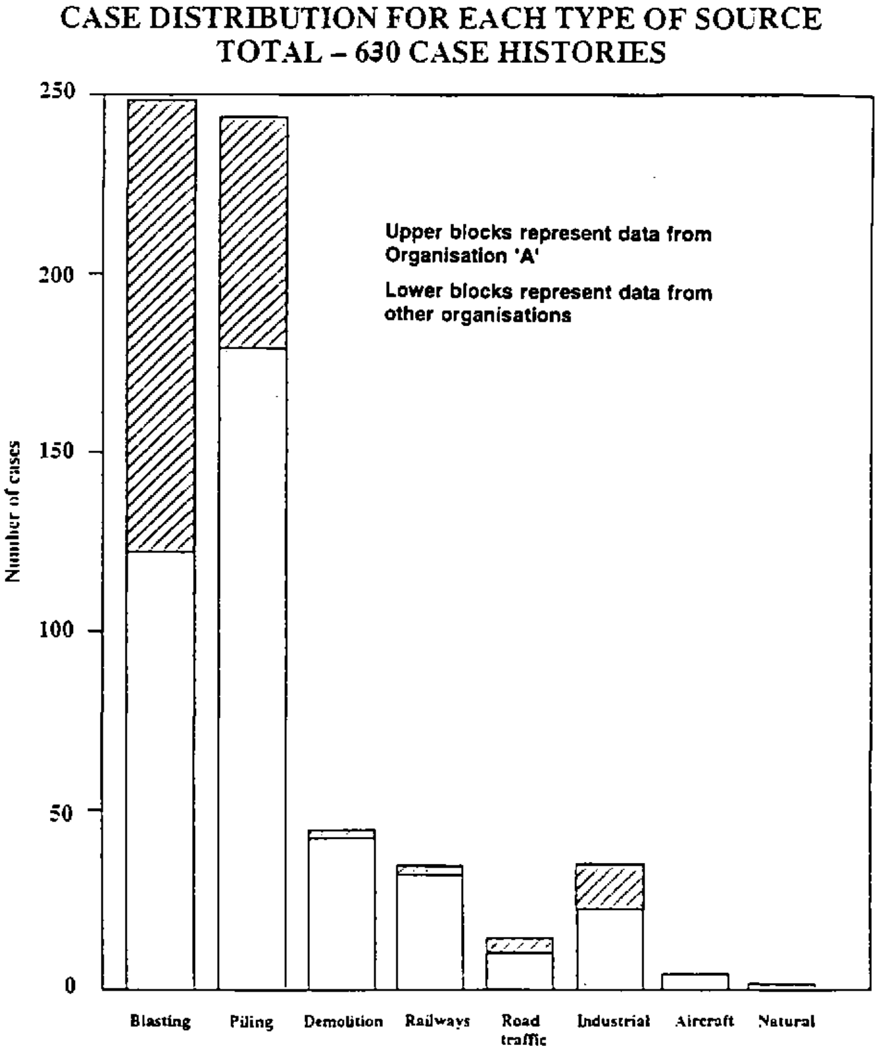

FIGURE 3 NUMBER OF CASES FOR EACH SOURCE TYPE

DISTRIBUTION OF ALL DATA – INCLUDING DAMAGE DATA

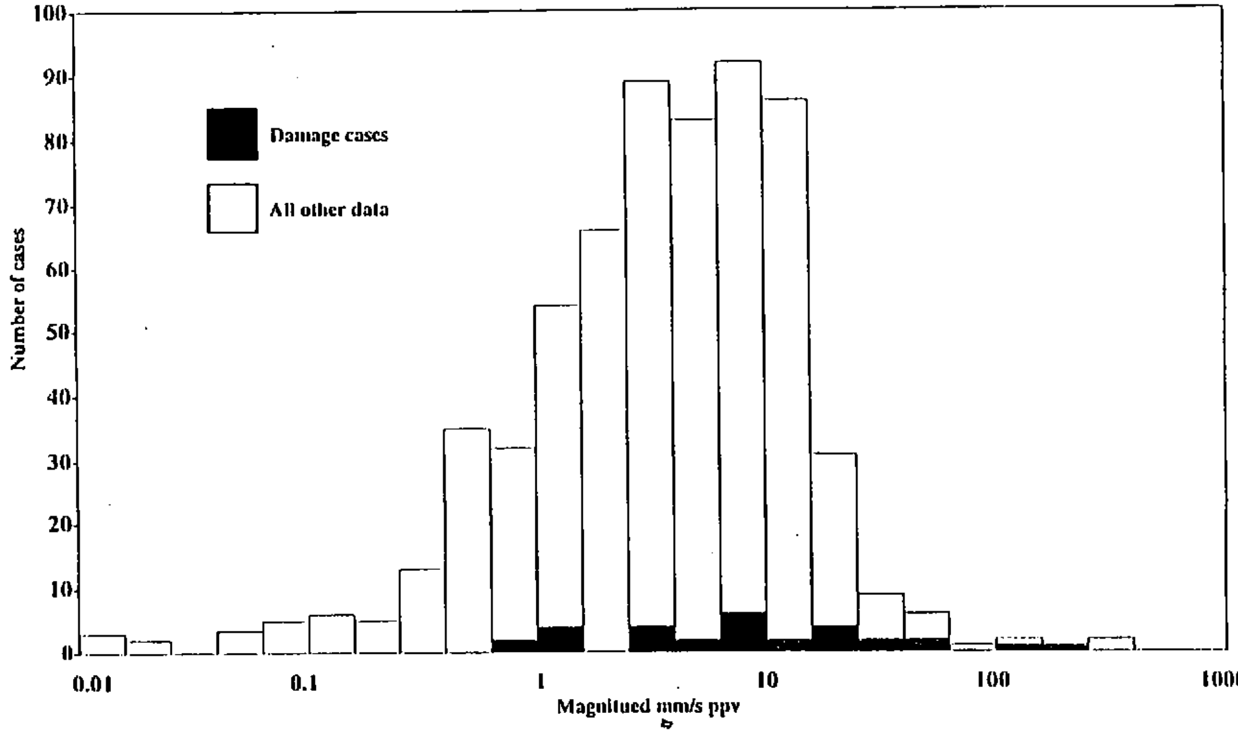

FIGURE 5 DISTRIBUTION OF ALL DATA

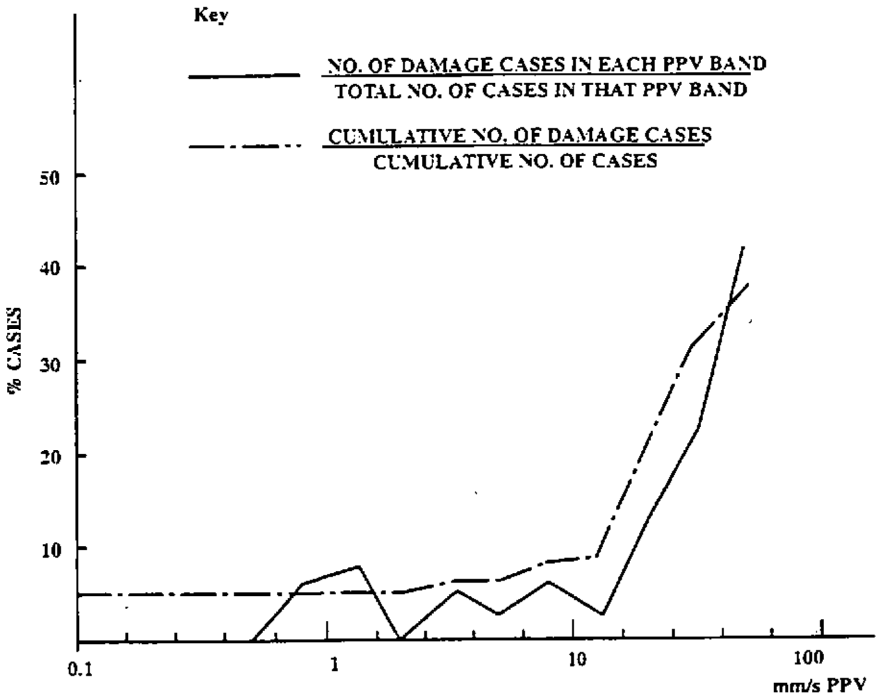

FIGURE 6 PROPORTION OF DAMAGE CASES IN SURVEY

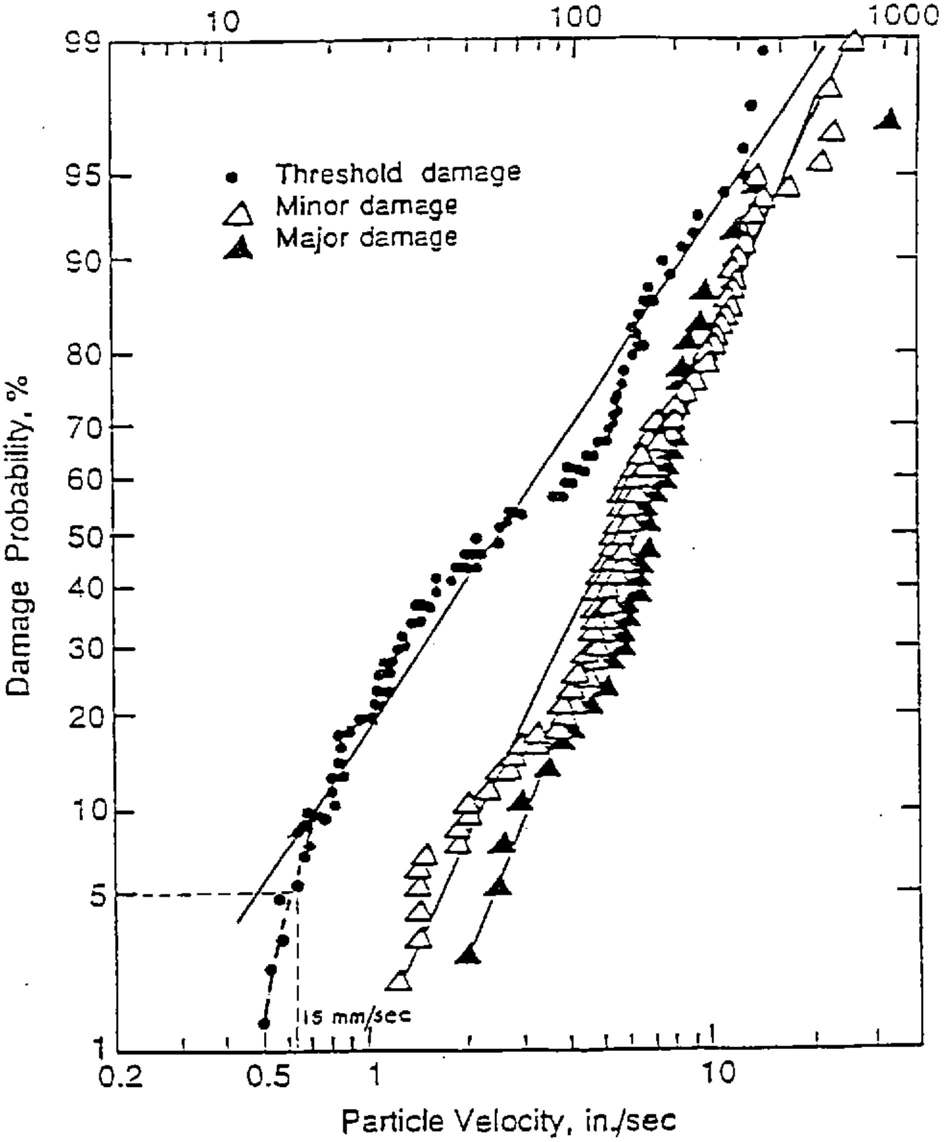

FIGURE 7 PROBABILITY DAMAGE ANALYSIS
Source: USBM RI 8507 (1980)

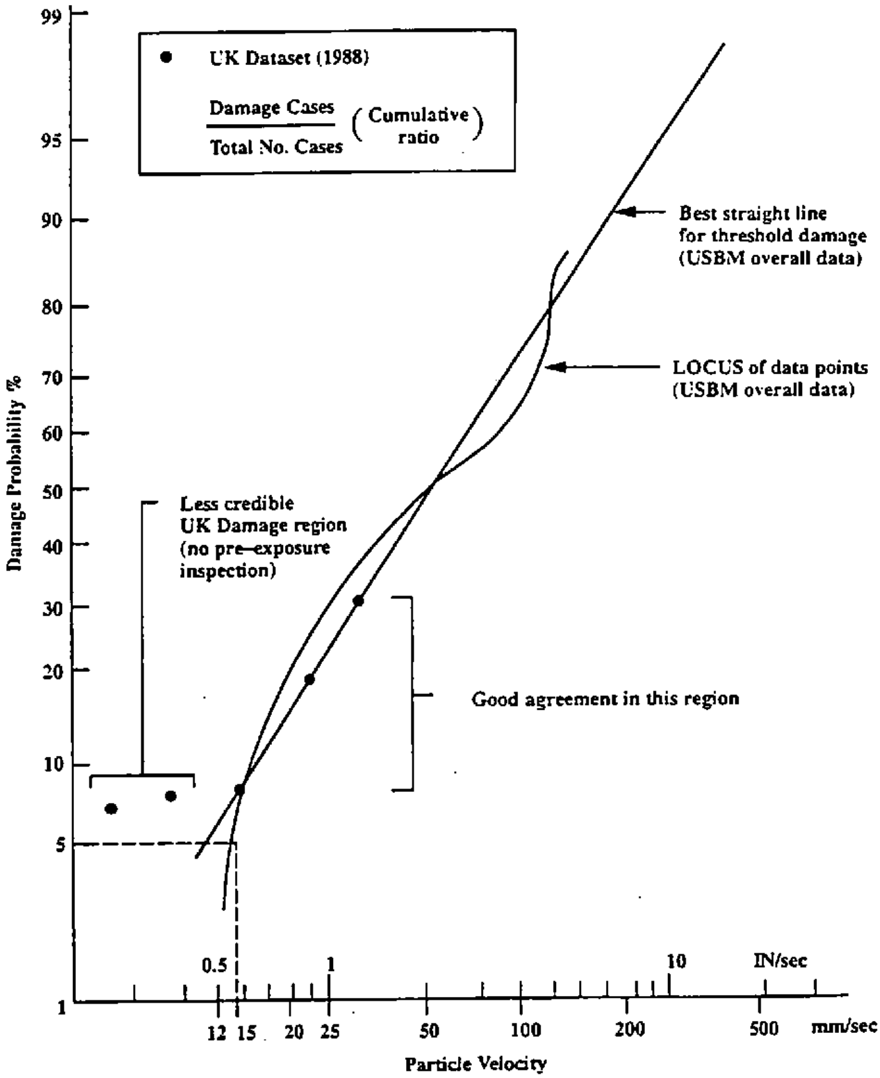

FIGURE 8 DAMAGE PROBABILITY DERIVED FROM UNCORRELATED UK DATA COMPARED WITH USBM OVERALL DATA

TABLE 4 TRANSIENT VIBRATION GUIDE VALUES FOR COSMETIC DAMAGE

Line	Type of building	Peak component particle velocity (mm/s) in frequency range of predominant pulse	
1	Reinforced or framed structures Industrial and heavy commercial buildings	50 at 4 Hz and above	
2	Unreinforced or light framed structures Residential or light commercial type buildings	4 Hz to 15 Hz	15 Hz and above
		15 at 4 Hz increasing to 20 at 15 Hz	20 at 15 Hz increasing to 50 at 40 Hz and above

NOTE 1. Values referred to are at the base of the building (see 6.3.)

NOTE 2. For line 2, at frequencies below 4 Hz, a maximum displacement of 0.6 mm (zero to peak) should not be exceeded.

ASSESSING VIBRATION IN BUILDINGS - BS 7385 : PART 2

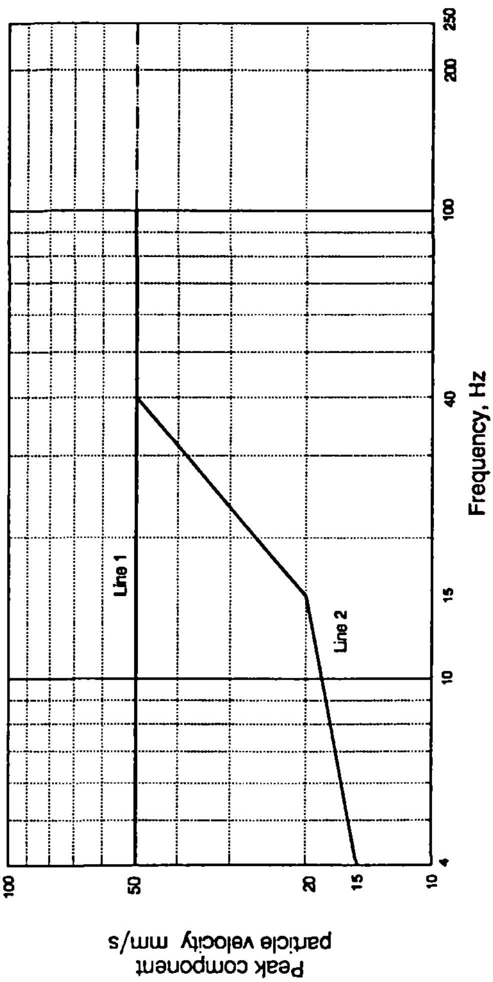

FIGURE 9 TRANSIENT VIBRATION GUIDE VALUES FOR COSMETIC DAMAGE