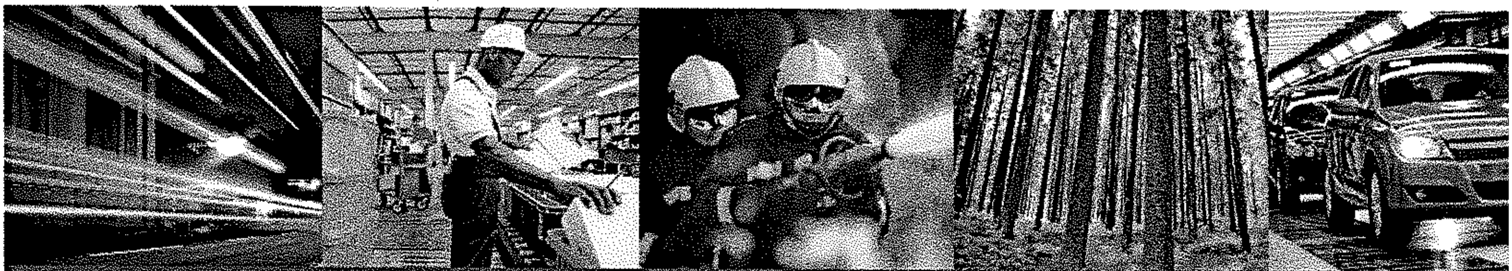
BS 5228-2:2009+A1:2014



BSI Standards Publication

Code of practice for noise and vibration control on construction and open sites –

Part 2: Vibration

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Contents

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 88, an inside back cover and a back cover.

Foreword

Publishing information

This part of BS 5228 is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 1 January 2009. It was prepared by Subcommittee B/564/1, *Noise control working group*, under the authority of Technical Committee B/564, *Noise control on construction and open sites*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

Together with BS 5228-1:2009, this part of BS 5228 supersedes BS 5228-1:1997, BS 5228-2:1997, BS 5228-3:1997, BS 5228-4:1992 and BS 5228-5:1997, which are withdrawn.

BS 5228-2:2009+A1:2014 supersedes BS 5228-2:2009, which is withdrawn.

Relationship with other publications

BS 5228 is published in two parts:

- Part 1: *Noise*;
- Part 2: *Vibration*.

BS 6472 gives detailed guidance on human response to vibration in buildings and BS ISO 4866:2010 covers the measurement and evaluation of structural vibration. BS 7385-2 contains guidance on damage levels from groundborne vibration.

An item dealing with the vibratory loading of structures, ISO/FDIS 10317, is being processed within ISO Technical Committee ISO/TC 98/SC/2, *Safety of structures*. This is being monitored by BSI.

Information about this document

This British Standard refers to the need for the protection against noise and vibration of persons living and working in the vicinity of, and those working on, construction and open sites. It recommends procedures for noise and vibration control in respect of construction operations and aims to assist architects, contractors and site operatives, designers, developers, engineers, local authority environmental health officers and planners.

Noise and vibration can cause disturbance to processes and activities in neighbouring buildings, and in certain extreme circumstances vibration can cause or contribute to building damage.

Noise and vibration can be the cause of serious disturbance and inconvenience to anyone exposed to it and in certain circumstances noise and vibration can be a hazard to health. Attention is drawn to the legislation summarized in Annex A.

BS 5228-2:2009 was a full revision of this part of BS 5228, and introduced the following principal changes:

- restructuring of the standard into two parts, one dealing with noise and one with vibration;
- updating of information relating to legislative requirements;
- updating of information relating to methods and equipment.

Text introduced or altered by Amendment No.1 is indicated in the text by tags [A1⟩ ⟨A1]. Minor editorial changes are not tagged.

NOTE Copyright is claimed in Tables E.1 and E.2. The copyright holder is the Transport Research Laboratory (TRL), Crowthorne House, Nine Mile Ride, Wokingham, Berkshire, RG40 3GA.

Use of this document

As a code of practice, this part of BS 5228 takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Any user claiming compliance with this part of BS 5228 is expected to be able to justify any course of action that deviates from its recommendations.

Presentational conventions

The provisions in this standard are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

1 Scope

This part of BS 5228 gives recommendations for basic methods of vibration control relating to construction and open sites where work activities/operations generate significant vibration levels, including industry-specific guidance.

The legislative background to vibration control is described and recommendations are given regarding procedures for the establishment of effective liaison between developers, site operators and local authorities.

Guidance is provided concerning methods of measuring vibration and assessing its effects on the environment.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

[A1) BS EN ISO 8041:2005, *Human response to vibration – Measuring instrumentation*

BS ISO 2041:2009, *Mechanical vibration, shock and condition monitoring – Vocabulary* (A1]

3 Terms and definitions

For the purposes of this part of BS 5228, the definitions given in [A1) BS ISO 2041:2009 (A1] and the following apply.

3.1 air overpressure
airborne pressure waves generated by blasting, produced over a range of frequencies including those which are audible and those which are below the lower end of the audible spectrum

NOTE Air overpressure can be quantified either as a pressure or as a level in linear (unweighted) decibels (dB).

3.2 amplification factor
motion measured at a given point (usually on the structure), divided by the motion measured at a reference point (usually at the base of the structure or on the foundation)

3.3 peak particle velocity (PPV)
instantaneous maximum velocity reached by a vibrating element as it oscillates about its rest position

3.4 overburden
material overlying the coal, or mineral or minerals to be extracted, including topsoil and subsoil

NOTE Economic deposits of other minerals can occur in the overburden.

3.5 piling
installation or removal of bored, driven and pressed-in piles and the effecting of ground treatments by vibratory, dynamic or other methods of ground stabilization

3.6 vibration dose value (VDV)
measure of the total vibration experienced over a specified period of time

NOTE The VDV can be determined for continuous, intermittent, occasional and impulsive vibration. It takes account of the magnitude of the vibration events and the number and duration of those events, to quantify the total vibration exposure. The VDV is given by the fourth root of the integral of the fourth power of the acceleration after it has been frequency-weighted and is defined as:

$$VDV_{b/d,\,day/night} = \left(\int_0^T a^4(t)dt \right)^{0.25}$$

where:

$VDV_{b/d,\,day/night}$ is the vibration dose value (in $m \cdot s^{-1.75}$);

$a(t)$ is the frequency-weighted acceleration (in $m \cdot s^{-2}$), using W_b or W_d as appropriate;

T is the total period of the day or night, in seconds (s), during which vibration can occur.

Further details of the VDV are given in BS 6472-1.

4 Community relations

Good relations with people living and working in the vicinity of site operations are of paramount importance. Early establishment and maintenance of these relations throughout the carrying out of site operations will go some way towards allaying people's fears.

It is suggested that good relations can be developed by keeping people informed of progress and by treating complaints fairly and expeditiously. The person, company or organization carrying out work on site should appoint a responsible person to liaise with the public. The formation of liaison committees with members of the public can be considered for longer term projects when relatively large numbers of people are involved.

NOTE The government has published research on the environmental effects of noise from blasting [1].

Vibration and air overpressure from blasting operations is a special case and can under some circumstances give rise to concern or even alarm to persons unaccustomed to it. The adoption of good blasting practices will reduce the inherent and associated impulsive noise: prior warning to members of the public, individually if necessary, is important.

5 Vibration and persons on site

5.1 Training

NOTE Attention is drawn to Regulation 8 of the Control of Vibration at Work Regulations 2005 [2], which requires employers to provide information and training where the risk assessment indicates a potential risk to the health of employees as a result of exposure to vibration [either hand–arm vibration (HAV) or whole body vibration (WBV)] or where the employees are likely to be exposed to vibration levels above the relevant action levels. The Regulations require all employees to be advised of the following, as part of their training:

a) the organizational and technical measures to be taken in order to comply with the requirements of Regulation 6;

b) the exposure limit values and action values set out in Regulation 4;

c) the significant findings of the risk assessment, including any measurements taken, with an explanation of those findings;

d) why and how to detect and report signs of injury;

e) entitlement to appropriate health surveillance under Regulation 7 and its purpose;

f) safe working practices to minimize exposure to vibration; and

g) the collective results of any health surveillance undertaken in accordance with Regulation 7 in a form calculated to prevent those results from being identified as relating to a particular person.

Operatives should be trained to employ appropriate techniques to keep site vibration to a minimum, and should be effectively supervised to ensure that best working practice in respect of vibration reduction is followed.

A programme of monitoring should be implemented to ensure that condition limits are not exceeded and that all the relevant recommendations are met.

5.2 Protection from vibration exposure

*NOTE With the advent of the Control of Vibration at Work Regulations 2005 [2], there are now specific legal duties imposed on employers in respect of both HAV and WBV (see Note to **5.1**). Useful guidance on these matters is contained within the Health and Safety Executive publications L140 [3] and L141 [4]. Applying the advice given in this guidance is expected, in the view of HSE, to ensure that the risks from HAV and/or WBV are properly controlled in accordance with the Regulations.*

Exposure to prolonged and regular work with high-vibration hand held tools can be a serious hazard to health. Workers using such equipment can suffer various forms of adverse effects, collectively known as hand–arm vibration syndrome (HAVS). The best known effect is vibration white finger (VWF) which is a prescribed industrial disease. Exposure to high levels of whole body vibration (WBV), e.g. for drivers of certain mobile plant in rough terrain conditions, can also be a serious hazard to health.

At present, there is no effective personal protective equipment to alleviate the exposure to HAV that is comparable to ear protectors in relation to noise. Operators of hand tools known to generate high levels of vibration are advised, however, to wear suitable gloves, especially when working in cold or damp conditions, as these conditions can exacerbate the symptoms of HAVS.

5.3 Vibration-induced stress

Vibration can interfere with working efficiency by inducing stress, by disturbing concentration and by increasing accident risk. Effects of vibration on persons on site are similar to, albeit far greater than, the effects on nearby residents, and the benefits of good control measures will apply equally on and off site.

6 Neighbourhood nuisance

6.1 Disturbing effects of vibration

Vibrations, even of very low magnitude, can be perceptible to people and can interfere with the satisfactory conduct of certain activities, e.g. delicate procedures in hospital operating theatres, use of very sensitive laboratory weighing equipment. Vibration nuisance is frequently associated with the assumption that, if vibrations can be felt, then damage is inevitable; however, considerably greater levels of vibration are required to cause damage to buildings and structures (see, for example, BS 7385-2) or to cause computers and similar electronic equipment to malfunction. Vibrations transmitted from site activities to the neighbourhood can, therefore, cause anxiety as well as annoyance, and can disturb sleep, work or leisure activities. In any neighbourhood, some individuals will be more sensitive to vibration than others.

The significance of vibration effects should be assessed in accordance with Annex B.

6.2 Site vibration descriptors

The peak particle velocity (PPV) is the simplest indicator of both perceptibility and the risk of damage to structures. [A1⟩ BS ISO 4866:2010 ⟨A1] and BS 7385-2 provide guidance on measurement, evaluation of effects on buildings, and damage levels, and are based upon use of the PPV.

The vibration dose value (VDV) is recommended in BS 6472 as the appropriate measure to evaluate human exposure to vibration in buildings in residential and other uses. The likelihood of adverse comment occurring from building occupants is used to evaluate the likely severity of effect.

For damage to structures, it is preferable to undertake measurements externally at the foundations; for human exposure, measurements are usually taken within a building at the position at which the occupant experiences the vibration. If vibration measurements are taken remote from the buildings or structures of concern, then they should be corrected for distance to those buildings or structures. When internal levels are required to be predicted, then a transfer function is needed to correct the external level to the internal location of interest. In order to obtain a typical value of PPV, and/or to derive a VDV representative of a 16 h daytime or 8 h night-time period, a representative number of cycles or operations should be monitored.

Whichever measure is used to describe vibration from the site, it should always be made clear to which period of time any particular value applies.

6.3 Issues associated with vibration effects and community reaction

A number of factors are likely to affect the acceptability of vibration arising from construction sites and the degree of control necessary. These are described as follows:

a) *Site location*. The location of a site in relation to vibration-sensitive receptors will be a major factor. The nearer a site is to sensitive premises, the more control that might be required upon vibration emanating from the site.

b) *Existing ambient vibration levels*. There is no known relationship between response and levels when comparing newly intruding and ambient vibrations. However, ambient vibrations are rarely significant or even perceptible and hence it is rarely necessary to consider the change in level.

c) *Duration of site operations*. In general, the longer the duration of activities on a site, the more likely it is that vibration from the site will prove to be an issue. In this context, good public relations and communication are important. Local residents might be willing to accept higher levels of vibration if they know that such levels will only last for a short time. It is then important that site operations are carried out according to the stated schedule and that the community is informed of their likely durations.

d) *Hours of work*. Sensitivity to vibration at different times of the day is far more complex than sensitivity to noise. The sensitivity of the human body to vibration varies according to the direction and frequency of the vibration. The guidance given in BS 6472 is useful, but when construction activities are of a temporary nature, situations will exist, both during the day and night, where vibration magnitudes above those generally corresponding to a low probability of adverse comment level can be tolerated. However, adverse community reaction is sometimes based upon concern over building damage, even when the vibration is just perceptible. It is therefore important to assure the community that vibration levels generally have to be of significant magnitude for even cosmetic damage to occur. (See also **8.6.7**.)

e) *Attitude to the site operator*. It is well established that people's attitudes to vibration can be influenced by their attitudes to the source or activity itself. Vibration from a site will tend to be accepted more readily by local residents, if they consider that the contractor is taking all possible measures to avoid unnecessary vibration. The attitude to the contractor can also be improved through good community liaison and information distribution and the provision of a helpline to respond to queries or complaints. The acceptability of the project itself can also be a factor in determining community reaction.

f) *Vibration characteristics*. The characteristics of vibration, e.g. whether it is continuous, intermittent or impulsive, can influence its acceptability.

g) *Effect on buildings*. This has been mentioned above [in item d)] but account should also be taken of the effect of vibration on buildings adjacent to the site. Guidance on the evaluation of these effects is provided in [A1⟩ BS ISO 4866:2010 ⟨A1], and guidance on damage levels from groundborne vibration is given in Clause **8** and BS 7385-2.

7 Project supervision

7.1 General

The intention throughout any construction programme should be to minimize the effects of site vibration whilst having due regard to the practicability and economic implication of any proposed control or mitigation measures.

Planners, developers, architects, engineers and environmental health officers can all assist in avoiding potentially excessive vibration levels. This can be achieved by giving careful consideration to the design of a proposed project, the processes and equipment implied by the design and the phasing of operations.

NOTE The Construction (Design and Management) Regulations 2007 [5] came into effect on 6 April 2007. They replace the Construction (Design and Management) Regulations 1994 [6] and the Construction (Health, Safety and Welfare) Regulations 1996 [7]. HSE publication L144 [8] provides practical guidance on complying with the duties set out in the Regulations.

The key aims of these are to integrate health and safety into the management of the project and to encourage everyone involved to work together to:

a) improve the planning and management of projects from the very start;

b) identify risks early on so that they can be eliminated or reduced at the design or planning stage and the remaining risks can be properly managed;

c) target effort where it can do the most good in terms of health and safety; and

d) discourage bureaucracy.

Developers, architects and engineers will need to know whether the processes they intend using are likely to be permitted. Therefore an early consultation should be made with local authorities in order to ascertain the limits or restrictions, if any, likely to be imposed. Annexes C and D give some guidance on levels of vibration from piling and blasting.

Local authorities should ensure that any vibration level limits or restrictions being imposed are necessary and practicable.

7.2 Works preparation

A project design should be so arranged that the number of operations likely to be particularly disturbing is kept to a minimum. Designers should also remember that project designs can have considerable influence upon operators' use of sites. Project designs should include the location of items such as haulage roads, crushing plants and compaction plant.

Appropriate investigations into ground conditions should be made when preliminary surveys are being carried out in order that consideration can be given to methods of working which could avoid problems.

A survey of the immediate neighbourhood surrounding a site should be undertaken to indicate the location of sensitive areas.

Guidance should be sought concerning recommended vibration levels for the neighbourhood surrounding a site, and concerning acceptance of the proposed methods of working, in very general terms, from the relevant authorities at the same time as approvals are being requested for the commencement of work. This procedure is intended to enable work to proceed smoothly.

When works involve a tender stage, details of consents or other restrictions should be given to tenderers as early as possible.

When a number of site operators will be working on one site, overall site operations should be coordinated. Preferred routes for off-site movement of vehicles should be established with the local highway authority and the police. Access traffic should be routed away from sensitive premises.

Tenderers for a project should select the most appropriate plant in order that limits will not be exceeded. They should also be aware of the extent of control measures that will be necessary so that appropriate cost allowances can be made.

Tenderers should satisfy themselves that proposed methods of working and phasing of operations will meet the local authority's requirements. They should be clear about this before submitting their tenders.

Tenderers should take due regard of the following before tendering:

a) site layout, e.g. location of static vibration sources;

b) types of machinery likely to be used and whether alternative types or techniques would achieve less disturbance;

c) the location and nature of adjacent vibration-sensitive areas.

7.3 Execution of works

NOTE The use of "best practicable means" (BPM) to control emissions can constitute a ground of defence against charges that a nuisance is being caused under Part III of the Control of Pollution Act 1974 [9] or Part III of the Environmental Protection Act 1990 [10].

All available techniques should be used to minimize, as far as is appropriate, the level of vibration to which operators and others in the neighbourhood of site operations will be exposed.

Measures which should be taken include the following.

a) The hours of working should be planned and account should be taken of the effects of vibration upon persons in areas surrounding site operations and upon persons working on site, taking into account the nature of land use in the areas concerned, the duration of work and the likely consequence of any lengthening of work periods.

b) Where reasonably practicable, low vibration working methods should be employed. Consideration should be given to use of the most suitable plant, reasonable hours of working for operations which might give rise to perceptible vibrations, and economy and speed of operations.

c) Vibration should be controlled at source and the spread of vibration should be limited, in accordance with Clause **8**.

d) Where processes could potentially give rise to significant levels of vibration, on-site vibration levels should be monitored regularly by a suitably qualified person appointed specifically for the purpose, particularly if changes in machinery or project designs are introduced. A method of vibration measurement should be agreed prior to commencement of site works, e.g. that specified in [A1) BS ISO 4866:2010 (A1].

e) On those parts of a site where high levels of vibration are likely to be a hazard to persons working on the site, prominent warning notices should be displayed (see also Clause **5**).

When potential vibration problems have been identified, or when problems have already occurred, consideration should be given to the implementation of practicable measures to avoid or minimize those problems. Local authorities, consulting with developers and their professional advisers or with site operators, will need to consider the extent of vibration control measures necessary to prevent the occurrence of significant problems, and will also need to consider whether the implementation of those measures will be practicable. Local authorities might wish to consider whether to specify quantified limits on site vibration and whether, additionally or instead, to lay down requirements relating to work programmes, plant to be used, siting of plant, periods of use, working hours, access points, etc.

The latter approach will often be preferable in that it facilitates the monitoring of formally or informally specified requirements, both for the authorities and for the site operators.

7.4 Emergencies

*NOTE Attention is drawn to Section 61 of the Control of Pollution Act 1974 [9], which requires provision to be made for emergencies (see **A.2.3.3**).*

In the event of any emergency or unforeseen circumstances arising that cause safety to be put at risk, it is important that every effort be made to ensure that the work in question is completed as quickly and as quietly as possible and with the minimum of disturbance to people living or working nearby. The local authority should be informed as soon as possible if it is found necessary to exceed permitted vibration limits because of an emergency.

8. Control of vibration

8.1 General

As outlined in Clause **1**, this part of BS 5228 gives recommendations for basic methods of vibration control relating to construction and open sites where work activities/operations generate significant vibration levels, including industry-specific guidance. Clause **8** is arranged so as to present generic recommendations, in **8.2**, **8.3** and **8.4**, followed in turn by the industry-specific guidance, which includes information relating to piling and ground engineering (**8.5**), the extraction of coal by open-cast methods and the surface extraction of other minerals (**8.6**). There is also a subclause (**8.7**) which addresses the issues relating to groundborne vibration and associated structure-borne noise, which arise from underground construction.

Construction and demolition activities can pose different problems of vibration control compared with most other types of industrial activity for the following reasons:

- they are mainly carried out in the open;
- they are of temporary duration although they can cause great disturbance while they last;
- the vibration they cause arises from many different activities and kinds of plant, and its intensity and character can vary greatly at different phases of the work;
- the sites cannot be excluded by planning control, as factories can, from areas that are sensitive to vibration.

If a site upon which construction or demolition work will be carried out involves an existing operational railway, special features which are significant in relation to vibration control have to be taken into account. Advice should be sought in such cases from the appropriate railway authorities.

Much of the vibration from construction and demolition sites is generated by machinery. Increased mechanization has brought about the use of more powerful machines, which have the potential to cause higher levels of vibration. It is now widely recognized that the vibration levels so generated are unacceptable in many instances and that reductions are necessary for the benefit of both the industry and the public.

8.2 Control of vibration at source

8.2.1 General

Vibration can be more difficult to control than noise, and there are few generalizations which can be made about its control. It should be borne in mind that vibration can cause disturbance by causing structures to vibrate and radiate noise in addition to perceptible movement.

8.2.2 Substitution

Where reasonably practicable, plant and/or methods of work causing significant levels of vibration at sensitive premises should be replaced by other less intrusive plant and/or methods of working.

8.2.3 Vibration isolation of plant at source

Vibration from stationary plant (e.g. generators, pumps, compressors) can, in some instances, prove disturbing when located close to sensitive premises or when operating on connected structures. In these instances, equipment should be relocated or isolated using resilient mountings.

8.3 Controlling the spread of vibration

NOTE The use of trenches to reduce transmitted vibration through the ground is described in ***8.5.3.3****.*

Where reasonably practicable, vibrating equipment should be located as far from sensitive premises as possible, and, if on a structure, not on one which is continuous with that of the sensitive premises. In some instances it might be possible to reduce transmitted vibration by cutting a structure to separate site work from sensitive premises. It is essential to take account of safety and structural issues before carrying out any work of this nature.

The demolition of tall or large structures, especially if explosives are used, can give rise to impulsive vibrations and air overpressure when the felled structures hit the ground. Further advice is contained in BS 6187.

8.4 Vibration control targets

NOTE 1 Section 60 of the Control of Pollution Act 1974 [9] specifies the matters to which local authorities will have regard when serving a notice imposing requirements to limit noise and vibration emission from sites.

NOTE 2 Annexes C and D give guidance on vibration levels produced by selected site equipment and activities and Annex E describes methods of estimating vibration. The information contained in these annexes is intended to assist with the prediction of the levels of vibration likely to emanate from a proposed construction site and to provide a useful reference when the setting of vibration limits is being considered.

All reasonably practicable means should be employed to ensure the protection of local communities and of people on construction sites, from detrimental effects of the vibration generated by construction operations. The means employed should be determined by local circumstances and can include vibration reduction measures for individual items or plant and machinery, the fixing of hours of work, the setting of noise or vibration limits or any other appropriate measures.

Those seeking to determine suitable vibration limits for construction operations should be aware of the particular noise problem that can occur when such operations take place in existing buildings that are either occupied or contiguous with occupied buildings. Vibration introduced directly into the structure by equipment such as breakers, hammers and drills might attenuate only slowly as it is transmitted through the structure and might therefore produce unacceptable levels of noise in rooms remote from the source. In particularly sensitive situations it might be necessary to use alternative techniques and equipment.

NOTE 3 See also ***6.3****.*

8.5 Practical measures to reduce vibrations from piling sites

8.5.1 General

NOTE The construction industry is generally innovative and constantly developing, and there might be proprietary systems available at the time of tender that were not known or available at the planning stage.

The most common form of vibration associated with piling is the intermittent type derived from conventional driven piling. Each hammer blow transmits an impulse from the head to the toe of the pile and free vibrations are set up. Sensors at a remote receiving point would indicate a series of wave disturbances, each series corresponding to one blow. (See also Annex F.)

When setting targets for maximum vibration levels (**8.5.2**), reference might need to be made to the existing baseline vibration levels, which should be measured prior to commencement of pile driving. This is particularly applicable on sites adjacent to roads carrying heavy commercial traffic, railway tracks and large industrial machinery. It is not uncommon for vibrations from such sources to mask vibrations from pile driving.

It is desirable that the planning process does not prohibit the use of any piling methods on the basis of vibration.

Where the predictions indicate that a particular piling method could prove marginal in terms of critical vibration levels, methods of alleviating the problem may be adopted as recommended in **8.5.3**.

8.5.2 Vibration levels

NOTE 1 Various empirical formulae have been proposed relating the intensity of vibration measured at the remote receiving point, to the distance between it and the source and the energy of the source. The use of such formulae enables a rough estimate to be made as a check on the acceptability of the proposed process from a vibration standpoint, prior to the commencement of the piling works. This estimate could also assist with applications under Section 61 of the Control of Pollution Act 1974 [9] for prior consent (see Annex A). For guidance regarding the prediction of expected vibration levels, see Annex E.

NOTE 2 See Annexes C and D for examples of vibration levels measured under various conditions throughout the UK.

The intensity of vibration at the point of interest will normally be a function of many variables including:

a) energy per blow or cycle;

b) distance between source and receiver;

c) ground conditions at the site, e.g. soft or hard driving and location of water table;

d) soil–structure interaction, i.e. nature of connection between soil and structure being monitored;

e) construction of structure and location of measuring points, for example:

   1) soil surface;

   2) building foundation;

   3) internal structural element.

In soft driving conditions, where a significant proportion of the energy per blow is directly used in advancing the pile, the intensity of vibrations transmitted to the environment is generally less than under hard driving conditions, where so much of the energy per blow is devoted to overcoming resistance to penetration that relatively little is available to advance the pile.

When driving piles in soft soils, the free vibrations set up are found usually to have a greater low frequency content than when driving into denser soils or rocks.

8.5.3 Vibration mitigation

8.5.3.1 Use of alternative methods

Piling and ground engineering processes are primarily selected on the basis of the ground conditions to be encountered, the loads to be supported and the economics of the system. Taking these constraints into account, the process should be selected that is least likely to give rise to unacceptable vibrations in particular circumstances. Examples would include the use of continuous flight auger injected piles, pressed-in preformed piles, auger bored piles, or possibly impact bored piles in preference to driven piles. Some form of ground treatment might also be possible, depending on soil conditions and loading requirements.

There are sometimes cases in which the majority of a site is amenable to a particular form of ground treatment or foundation construction but where a limited area is too close to existing structures or services to permit unrestricted use of the process. For example, from Table D.3 (see Annex D) it can be deduced that dynamic compaction using large tamping weights should be kept a reasonable distance away from such features. If a small intervening area remains to be treated, this may be done using one of the vibro processes of ground treatment. Similarly, the majority of a site may be piled using the driving process, leaving a minority to be completed with continuous flight auger injected piling.

It should be noted that a change in method part of the way across the site might result in a mismatch in subsequent foundation behaviour. The engineering implications of any such changes should be taken into account prior to construction on site.

When piling is to be installed close to slopes, vibration of any form can cause movement of the slope material.

When the pile type is chosen, care should be taken to avoid substituting the risk from vibration, pore pressure changes and soil displacement associated with driven piling and other systems which generate vibrations, by threats to stability resulting from uncontrolled soil removal or the release of ground water.

It is often advantageous to carry out controlled trials to establish a safe method of working, from observations of vibration intensity, of the onset of local distress to the soil face and of changes in line and level.

NOTE The extraction of piles and their ancillary equipment can also generate vibration.

Where doubt about the loss of stability remains, action should be taken either to phase the work so that piling can be completed before earthworks are carried out, or to retain the soil effectively to allow piling to take place safely.

Where piling is required near to electronic installations (see Annex B, **B.5**), an important consideration is the likely frequency range of the piling vibrations. An example from one major manufacturer quotes permitted levels for intermittent vibrations varying between 50 mm·s^{-1} at 8 Hz and 10 mm·s^{-1} at 40 Hz, a frequency range which covers much of that associated with piling in soils. These criteria are judged to apply to electronic equipment correctly installed on the ground floor of a building.

Electronic equipment is not as fragile as is often believed and, with care, piling need not pose a threat to the continued safe use of a typical electronic installation. Extra care might be needed if the installation is mounted on a suspended floor which might accentuate the level of vibration.

8.5.3.2 Removal of obstructions

Obstructions constitute a hindrance to progress and exacerbate the transmission of vibration, especially where they occur at shallow depths. Obstructions known to exist, e.g. old basement floors, old foundations, timbers, etc., should be broken out at pile or stone column positions and the excavation backfilled. Where an unexpected obstruction is encountered, it might be preferable for piling to be halted at that position until such time as the obstruction can be dealt with, rather than attempting prolonged hard driving.

Coring through existing piles and foundations is becoming more common on urban sites. Vibrations resulting from this process will need to be considered carefully.

8.5.3.3 Provision of cut-off trenches

A cut-off trench can be regarded as analogous to a noise screen, in that it interrupts the direct transmission path of vibrations between source and receiver. There are serious limitations to the efficacy of trenches. For maximum effect the trench should be as close to the source or to the receiver as possible. The trench should have suitable dimensions to mitigate vibration adequately; specialist advice should be sought to determine the appropriate dimensions. With normally available excavators on site, trench depths are seldom in excess of 4 m or 5 m.

A trench constitutes a safety hazard. Even if the ground is self-supporting, a flexible support mechanism, e.g. bentonite suspension, might be needed. Care should be exercised in designing and locating the trench to avoid any loss of support to the structure it is intended to protect or to the piles being installed. Care should also be taken to ensure that the stability of the piling equipment is not endangered by the presence of the trench.

The wall of the trench closest to the piling operation might suffer progressive collapse during the course of the works. Provided that all appropriate hazards are identified and managed, such collapse might be acceptable as an energy releasing mechanism.

At the conclusion of the relevant piling operations the trench should be appropriately backfilled.

Specialist advice should be sought prior to constructing cut-off trenches, as this option does not provide appropriate mitigation for all vibration problems.

8.5.3.4 Reduction of energy input per blow

Consideration of the relationships described in Annex E suggests that there is a dependence of the PPV on the energy input for hammer-driven piles. It might therefore be possible to reduce the level of vibration caused by piling by reducing the energy input.

The penalty for adopting this method is that more blows at lower energy will be needed to drive the piles to a required depth. The trade-off will not necessarily be linear owing to other losses in energy in the system. Use of this mitigation method, combined with vibration monitoring, might enable driving piles close to buildings with shallow foundations or in the vicinity of shallow buried services, by starting the drive with low hammer drops, subsequently increasing the energy as the toe of the pile reaches the founding stratum at greater depth.

Although in general terms it is accepted that vibrations at any level can contribute to fatigue mechanisms in structures, the relative importance of vibration intensity and number of cycles at that intensity is not sufficiently understood. Under the appropriate circumstances, however, it might be more acceptable, or even preferable, to reduce the energy per blow, thus limiting the PPV but sustaining a longer period of pile driving. The effect of this approach on the degree and duration of disturbance to the building's occupants might also need to be taken into account.

NOTE Special arrangements might be needed where piles are driven to a set. Driving to a set entails counting a number of blows from a standard height of drop (standard for the particular piling system) for a given (small) penetration, or by measuring the penetration obtained after a given number of blows from the standard height of drop. It should be borne in mind that set might not be achieved when using the lower drop height initially chosen to reduce vibration magnitude.

8.5.3.5 Reduction of resistance to penetration

8.5.3.5.1 Pre-boring for driven piles

When piles are to be driven and there is the risk of excessive vibrations emanating especially from the upper strata, the problem can sometimes be reduced by pre-boring. This process removes some of the soil which would otherwise have to be displaced in the early stages of pile driving. There is some evidence to suggest that the final level of vibration during driving would not be reduced, although there would be a reduction in the number of blows needed to achieve the proper penetration.

A variant of this procedure which can be used with top-driven cast in place piling is to commence by driving the tube open-ended. A plug of soil is formed within the tube, which is then withdrawn and the plug is removed. This can be repeated several times before the shoe is fitted and the tube driven closed-ended in the normal manner.

8.5.3.5.2 Mudding in for rotary bored piles

Whilst pre-boring is used in the construction of rotary bored piles in order to reduce the resistance of penetration of temporary casing, it is often coupled with mudding in to reduce the risk of collapse of the sides of the bore.

Following normal pre-boring, a small quantity of bentonite slurry is added to the borehole and the auger is rotated rapidly in order to stir up the slurry and any collapsed material from the unlined sides. The casing is then offered into the hole, its penetration being assisted by the lubricating action of the mud slurry. Depending on conditions the final seating of the casing can be assisted either by use of a twister bar (the casing being rotated in), or by tapping with a heavy casing dolly or by using a vibrator. The use of these latter two items should, however, be minimized.

8.5.3.5.3 Adding water to the bore hole for impact bored piles

The level of vibration from impact bored piling is generally considered acceptable and the method is occasionally used on confined sites adjacent to existing structures. The level of vibration increases with the resistance to boring and particularly when the boring tool fails to make measurable progress, e.g. in dense dry gravel. Progress can be increased by adding water to the bore, but great care is needed to ensure that the casing is advanced in pace with the boring tool and that excessive use of water is avoided to reduce overboring and the consequent risk of undermining adjacent structures.

8.5.3.6 Excavation under support fluid

An alternative procedure for bored piles using very long casings where there are substantial depths of water bearing sands and silts, is to drill the piles under support fluid.

It might then be possible to restrict casing to a relatively short length, thereby avoiding the need to resort to the use of either vibratory or percussive dollies for insertion or withdrawal.

8.5.3.7 Avoidance of shear leg contact with sensitive structures

Tripod impact bored piling rigs can impart vibrations and shocks through the shear legs. Where, as is often the case, there is a confined working area for a tripod rig, care should be taken in setting up the rig at any pile position, to avoid having one of the legs or its support in direct contact with any adjacent building which might be sensitive to vibrations.

8.5.3.8 Removal of the plug when using casing vibrators

Vibratory drivers have difficulty in penetrating dense cohesionless soils (see Annex F). Where such a machine is used to insert a casing into a stratum of medium dense to dense granular soil, a plug of this soil will accumulate inside the casing. The vibrator will now be confronted with additional resistance, thus slowing penetration and probably accentuating environmental vibration levels.

Provided the boring rig has a sufficiently high rotary table, it should be used to drill out the plug at intervals between short periods of vibratory driving. This procedure is expected to substantially reduce the total amount of time needed for use of the vibrator.

8.5.3.9 Bottom-driving

Bottom-driving might result in lower vibration levels than top-driving. The method can be applied to some permanently cased piles and some specialized cast-in-place systems.

The process is quieter than its top-driven counterpart; however, any reduction in vibration intensity might be associated with the generally slower rate of production.

8.5.3.10 Use of variable moment vibrators

Vibrators operate through a system of contra-rotating eccentric weights that are arranged such that the dynamic forces generated by their rotation are vertically aligned. During the start-up and run-down periods of operation, the rotational frequency undergoes continuous change between the static and steady-state operating frequency. Groundborne vibration is often found to be higher during the start-up and run-down phases than during steady driving at the full operating frequency.

Research undertaken by TRL [11] has shown that this is related to differences in the attenuation rates of different frequencies of vibration: when the operating frequency of the vibrator corresponds with the preferred propagation frequency of the ground, the vibration is attenuated less with distance than at other, particularly higher, frequencies. The transient phases of operation can therefore affect a larger area than the vibration during steady state driving. Furthermore, the frequency sweep can pass through the resonance frequencies of elements of structures (such as floors and ceilings), leading to temporarily elevated levels of vibration.

There are clearly advantages in avoiding these transient phases of operation where groundborne vibration might be an issue. Some manufacturers supply vibrators that can be operated such that the system of eccentric weights is balanced during start-up and run-down so that all forces are equal and opposite. Once the operating frequency is reached, the phase is shifted so that vertically aligned vibration is generated as normal. Groundborne vibration is therefore largely eliminated during the start-up and run-down phases.

8.6 Practical measures to reduce vibration from surface coal extraction by opencast methods and surface mineral (except coal) extraction

8.6.1 General

Both opencast coal sites and other surface mineral extraction sites can pose a greater diversity of problems of vibration control compared with most other types of industrial activity for the following reasons.

a) Apart from some ancillary operations, they are carried out entirely in the open and can extend over a wide area.

b) They are of variable duration from a few months to several years or even decades, and in some cases sites in adjacent areas can follow one another in succession over a prolonged period.

c) A wide variety of activities are carried out involving the following phases:

   1) geological and geotechnical exploration;

   2) preliminary operations to establish the site;

   3) soil stripping and removal of overburden;

   4) for opencast coal, coaling, coal preparation, storage and dispatch; for other surface minerals, processing, e.g. washing, crushing and screening, transportation of material within sites and to markets; blasting might be required to extract coal or other minerals;

   5) backfilling and final site restoration;

   6) rehabilitation of final land form to public amenity, agriculture or other subsequent development.

d) A wide range of earth-moving and specialized plant is employed, the use of which varies significantly at different phases and times and at different heights and depths within the site. The intensity and character of any vibration and/or air overpressure can vary at different phases of work, at different times and under differing conditions of, for example, topography, geology, climate and methods of operation.

e) Coal and other minerals can only be worked where suitable resources exist. Resources might be present in close proximity to premises sensitive to vibration. Under these circumstances, such premises should be protected as far as is practicable from the adverse effects of vibration.

The highest levels of vibration on these sites are generally only associated with blasting activities, although at closer range vibrations can be experienced from material processing, transport and the operation of large earthmoving machinery. Measures to control vibration are generally necessary where sites are located in the vicinity of sensitive premises, for the benefit of both the public and the industry.

Blasting might be required at opencast coal sites, but only occurs at a proportion of other surface mineral extraction sites, generally those producing crushed rock. There are particular characteristics of blasting which require specific consideration of vibration issues. Blasting creates vibration which is of very short duration, with a frequency of events varying from a small number per year to several times per day, depending on the nature and size of the extraction operation.

In addition to coal, a wide variety of different minerals is produced in Britain by surface extraction methods. The methods of working vary greatly according to the type of mineral, its geology and location and the end uses for which the mineral is intended. The nature of any impact from vibration therefore needs to be considered in the context of the relevant site-specific factors.

A typical mineral extraction operation involves stripping of topsoil and removal of overburden, excavation and processing of the material to be extracted, transportation of material within the site and to markets and subsequent restoration of the land.

Prior to making an application for planning permission, an applicant should discuss with the Mineral Planning Authority (MPA) and the appropriate department of the local authority (see Annex A) the predicted vibration levels from the proposed site and the control measures to be implemented. This will highlight at an early stage any vibration issues that need to be addressed. The predicted vibration levels and proposed control measures should be included in the application documentation, which should, where appropriate, also contain information on the typical existing background levels. Where a formal environmental assessment is undertaken, vibration will normally be taken into account.

Local residents and other interested parties should also be consulted at this stage.

8.6.2 Site planning

In planning the working of the site, account should be taken of the effect of the proposed working method and site layout on adjacent sensitive premises. Where necessary, alternative methods or arrangements which have the least impact of emissions of vibration should be employed if economically viable.

8.6.3 Location of site elements

With due consideration of the topography of the area and natural screening effects, care should be taken in the siting of the following:

a) access points;

b) limit of excavation;

c) coal screening and washing plants, or other mineral crushing, screening and washing plants, as appropriate to the site;

d) pumps, generators and static plant;

e) stocking areas and loading facilities;

f) off-site coal or other mineral haulage routes.

NOTE The location and design of access points have to be agreed with the highway authority and the Mineral Planning Authority.

Access points should be located with due regard to the proximity of vibration-sensitive premises.

The limit of excavation is determined by a wide range of geological and engineering constraints such as the location, nature and quality of the coal or other mineral, the characteristics and stability of the strata and the existence of faults and other features.

Site amenities, plant yards, maintenance areas, coal screening/washing plants or other mineral crushing/screening and washing plants, stocking and loading facilities should be sited as far from vibration-sensitive premises as practicable.

Where the processed coal or other mineral is to be transported from the site by road, the route should be carefully selected to minimize the impact on vibration-sensitive premises even if this results in an increased haulage distance.

8.6.4 Working methods

It is important to consider the methods of working to be adopted including the sequence and phasing of activities on site. Activities that are undertaken close to vibration-sensitive properties should be programmed where practicable over a short period of time appropriate to local conditions. A common sense approach to such activities will help minimize the potential for any adverse environmental impacts. The following factors, which can have particularly significant effects, should, where relevant, be taken into account:

a) depth of the coal seams or other mineral deposits;

b) direction of working;

c) plant to be employed;

d) working hours;

e) rate of production;

f) use and control of blasting, including timing and frequency.

Once the limit of excavation and the maximum depth of the coal seams or mineral deposits to be extracted have been determined (see **8.6.3**), a direction of working and phasing of operations should be deployed that reduces the transmission of vibration from the site.

There is a wide range of variables that influence these activities, therefore it is not possible to be prescriptive for individual sites.

8.6.5 Selection of plant

The characteristics of vibration emissions from each item of plant, and their collective effect, should be assessed during the selection process for the acquisition of plant. Where practicable, plant should be selected which will have the least impact in terms of vibration.

8.6.6 Deployment of plant

The movement of plant on and off the site should be restricted as far as practicable to within the agreed working hours for the site.

8.6.7 Hours of work

NOTE See also **6.3***d).*

For any operation where vibration might have an adverse effect on the occupants of sensitive premises, working hours should be restricted in preference to the sterilization of coal reserves or other mineral resources. Such restrictions should only be imposed where they are necessary. It might in some circumstances be reasonable to limit particular operations or working phases to certain durations or times of the year, where this does not unduly conflict with the operation of the site. Alternatively it might be more appropriate, especially when dealing with established operations, to take other practical measures for vibration reduction (see **8.6.4**). Coal or other mineral haulage by road from such sites should be limited to between 07.00 h and 19.00 h, unless local circumstances require otherwise.

8.6.8 Site management

8.6.8.1 General

Good site practice depends upon suitably trained or experienced site operatives. Appropriate supervision and a commitment by all concerned to keep vibration to a minimum can provide a cost-effective way of achieving the objectives of this part of BS 5228.

8.6.8.2 Operatives

Operatives should be familiar with the relevant conditions of the planning permission, details of which should be available for inspection on site at all times. The site should be operated in accordance with these conditions at all times and where practical difficulties arise discussion should be sought with the relevant authority as soon as these become apparent.

8.6.8.3 Supervision and maintenance

It is likely that vibration will be an important factor in any opencast pit or quarry plan and/or environmental management, which might also involve monitoring of site performance or more detailed audits carried out by site staff or other appropriate parties. Records should be kept of any complaints received or other breaches of the controls or planning conditions relevant to vibration, in order to assist effective site management.

Site supervision and maintenance are essential in ensuring that throughout its life, operations are carried out as they were intended. Plant and machinery (including measurement equipment) should be maintained in good working order and used in accordance with the manufacturer's instructions. Special attention should be paid to any aspects which might affect the vibration likely to arise.

8.6.8.4 Transport routing

Measures should be put in place to ensure that where it is intended that both on-site and off-site lorry traffic should follow a particular route, sufficient information is provided to all drivers and other relevant staff to ensure that they are aware of their responsibilities. This can be provided by on-site signage or through other information handed to drivers.

8.6.9 Practical measures to reduce vibration and air overpressure from blasting

8.6.9.1 General

Most complaints of vibration relate to blasting. Blasting should only be used where there is no viable alternative. Groundborne vibration can lead to concern being expressed by residents around opencast sites, usually over the likelihood of damage to property. Good public relations have been shown to reassure the public of the fact that normal production blasting has not been found to damage property, and that even the most cosmetic of plaster cracking is extremely unlikely. In addition, contacting owners of sensitive properties to advise of imminent blasting can further help promote harmony with the public. It is good practice to publicize times when blasting will occur and to avoid blasting at other times whenever possible.

Air overpressure from blasting comprises transient airborne pressure waves which can be heard and felt. Air overpressure can be influenced by meteorological conditions over which operators have no control. Although air overpressure can be affected by the total quantity of explosives deployed in a blast, there is a balance to be struck between a smaller number of large blasts and a larger number of small blasts. Public relations have an important role to play in determining the optimum balance between size and frequency of blasting.

8.6.9.2 Vibration and air overpressure reduction

NOTE 1 Care needs to be taken to avoid damage to cave systems and underground passageways.

NOTE 2 Further information on ground vibration and air overpressure is given in Annexes F and G respectively.

Practical measures, including good blast design, that have been found to reduce air overpressure and/or vibration are:

a) taking particular care with the development of faces and with trial blasts at a quarry or opencast coal pit, as anomalous vibration levels might be produced when there is no free face to relieve the energy produced;

b) ensuring appropriate burden to avoid over or under confinement of the charge;

c) accurate setting out and drilling;

d) appropriate charging;

e) appropriate stemming with appropriate material such as sized gravel or stone chippings;

f) using delay detonation to ensure smaller maximum instantaneous charges (MICs);

g) using decked charges and in-hole delays;

h) blast monitoring to enable adjustment of subsequent charges;

i) designing each blast to maximize its efficiency and reduce the transmission of vibration;

j) avoiding the use of exposed detonating cord on the surface in order to minimize air overpressure – if detonating cord is to be used in those cases where down-the-hole initiation techniques are not possible, it should be covered with a reasonable thickness of selected overburden.

8.6.10 Coal disposal sites

After coal is excavated from an opencast site it is sometimes taken to a coal disposal site. This can be located within an opencast site, adjacent to an opencast site or at some distance, near main line rail and road facilities, and can serve more than one site. At a coal disposal site any, all or a combination of the following can take place: coal washing, crushing, screening, blending, storage in hoppers or on the ground in bunds and dispatch from the disposal point by rail or road vehicles.

Most of these activities generate vibration. The major sources are the crushing and screening processes, the reception and disposal hoppers, mobile site plant and road and rail traffic.

Coal disposal sites are areas of major industrial activity which might need to be located at distance from vibration-sensitive areas.

8.6.11 Limitations on emissions of vibration from sites

NOTE Additional conditions might also be imposed by the Secretary of State or Mineral Planning Authority as appropriate. (A1) Guidance for noise from surface mineral works is given in the Minerals section of the web-based documents that form the Planning Practice Guidance [13]. (A1)

Opencast coal and other surface mineral extraction and associated works can take place in remote to semi-urban area conditions. Each site and situation should be analysed for vibration control on its own merits. When the site is adjacent to vibration-sensitive premises it might be necessary to impose conditions including specific vibration limits.

Guidance on criteria for the setting of vibration control targets is given in Annex B.

Limitations on working hours for the site, or part of it, and the restriction of the activities most likely to cause vibration to less sensitive times or days, can be employed as a means of limiting the impact of vibration from opencast coal and other surface mineral sites.

8.7 Groundborne vibration and consequent noise from sub-surface construction activities

Where construction works take place entirely underground and away from access or ventilation shafts, airborne noise is often completely attenuated by the overlying ground or structures. If the construction activity generates vibration at source, then both groundborne vibration and groundborne noise (or structure radiated noise) can be prominent effects experienced at the surface and within overlying buildings. Groundborne noise generated within a building is predominantly low frequency in nature and can be caused by the vibration of all the internal surfaces of that building. As such, the effects can be particularly intrusive and potentially inescapable and, when combined with the simultaneous experience of perceptible vibration, can give rise to higher magnitudes of adverse comment, at a given level, than might be expected from available dose response data for more typical environmental noise sources. These particular features mean that the noise and vibration effects of underground construction activities can be a significant environmental risk to project developers.

Activities which can give rise to appreciable vibration and groundborne noise include tunnel and cavern construction. Tunnelling techniques vary considerably but known sources of groundborne noise include tunnel boring machines, road-headers and excavators; tunnel segmental lining placement; hydraulic drilling; use of hydraulic hammers for cavern mining; limpet vibrators; and drill-and-blast operations. Depending on the progress rates and techniques employed, these effects can be relatively short-lived but might expose a sensitive receiver to high magnitudes of vibration and/or groundborne noise.

For large tunnelling projects, the transportation of excavated material from the tunnel face can be undertaken by conveyor, by lorry or by the use of a temporary railway system. These transportation systems might need to operate for several months or even years on a 24 h basis and therefore might become potential long-term concerns in relation to groundborne noise and vibration generation. A temporary railway might need to be designed from the outset to control groundborne noise and vibration generation to a similar specification, and using similar techniques, as a permanent underground railway.

NOTE Research undertaken by TRL [11] provides guidance on calculating first estimates of potential vibration and groundborne noise levels from mechanized bored tunnelling works.

The mechanisms which give rise to the propagation of vibration through media such as soil are complex. The magnitude of vibration is determined by the characteristics of the vibration source, the properties of the excavated ground, and the ground between the vibration source and receiver. Multi-layered soils and/or the presence of deep piled building foundations can further complicate and modify magnitudes and estimates. As such, it is inappropriate to provide definitive generic guidance on the likely magnitudes of groundborne noise and vibration that might be expected as a result of a particular construction technique. Estimation of the likely noise and vibration effects from sub-surface construction activities based solely on consideration of previous case studies should therefore be undertaken with caution. Calculating groundborne noise and vibration is highly specialized, and expert advice should be sought if a high degree of confidence in the predicted levels is required.

There are no standards which provide objective criteria for the assessment of the significance of groundborne noise during sub-surface construction, and expert advice should be sought on appropriate guideline levels for a specific project which take into account the duration of the project, the frequency of any events, the potential magnitude of groundborne noise, the numbers and sensitivity of buildings affected, the adopted construction technique and other relevant factors.

The Office of Planning and Environment of the US Federal Transit Administration (FTA) has published groundborne noise impact criteria for the general assessment of transit schemes [14]. The criteria vary according to the number of groundborne noise events likely and the sensitivity of the receiving buildings. Although these criteria have been developed primarily for railway applications, they may be used as guidance for the screening or assessment of sub-surface construction activities. For frequent events, a guide maximum sound pressure level of 35 dB(A) using the "slow" time constant (inside residences and buildings where people normally sleep) is given in the FTA document for assessing the impact of long-term operation of a transit system. In some circumstances, the unfamiliar character and unknown duration and origin of construction groundborne noise can justify the application of lower guide levels than would be appropriate for long-term transportation sources, particularly if used to assess the need for mitigation initiatives.

Mitigation options for mechanized tunnelling activities are limited. In some circumstances, it might be possible to limit working hours, but in every case where the risk of widespread unacceptable disturbance exists, a comprehensive and informative community relations programme should be formulated and implemented well in advance of the approaching works. This can be particularly effective for tunnelling works, since the source is not visible and the effects are quite unlike those to which the general public is commonly exposed, which exacerbates concerns. On certain tunnelling projects it might be possible to control the vibration at source by limiting the rotational speed of the cutting face or the thrust force and progress rate of the tunnel boring machine.

Mitigation options for a temporary construction railway include restricting the speed of the vehicles; controlling the wheel/rail roughness by grinding or conditioning; limiting and avoiding misaligned or worn rail joints; and the provision of resilient layers beneath the rails and/or beneath an entire temporary sleeper assembly.

In some circumstances, the exposure to groundborne noise and vibration at residential dwellings can render the building unoccupiable and can warrant the temporary relocation of occupants, particularly when night-time working is required.

9 Measurement

NOTE Guidance on measurement of vibration for assessing human disturbance is given in BS 6472, and for building damage in [A1) *BS ISO 4866:2010* (A1].

9.1 Monitoring

In order to ensure optimum control of vibration, monitoring should be regarded as an essential operation. In addition to vibration monitoring, static tell-tale measurements can also be useful. Precision tell-tales are capable of registering longer term trends and can provide early warning of impending structural problems. Failures, sometimes catastrophic, can occur as a result of conditions not directly connected with the transmission of vibrations, e.g. the removal of supports from retaining structures to facilitate site access.

Where site activities other than pile driving can affect existing structures, a thorough engineering appraisal of the situation should be made at the planning stage. Information on monitoring of vibrations is included in Annex F.

9.2 Methods of measurement

9.2.1 General

The method selected to characterize building vibration will depend upon the purpose of the measurement and the way in which the results are intended to be used. Although a measurement technique which records unfiltered time histories allows any desired value to be extracted at a later stage, it might not be strictly necessary for the purpose of routine monitoring.

9.2.2 Positions

NOTE Information is given in [A1] *BS ISO 4866:2010* [A1].

The number of measurement positions will depend upon the size and complexity of the building.

When the purpose is to assess the possibility of structural damage, the preferred primary position is in the lowest storey of the building, either on the foundation of the outer wall, in the outer wall, or in recesses in the outer wall. For buildings having no basement, the point of measurement should be not more than 0.5 m above ground level. For buildings with more than one storey, the vibration might be amplified within the building. In the case of horizontal vibration, such amplification might be in proportion to the height of the building, whereas vertical vibration tends to increase away from walls, towards the mid-point of suspended floors.

It might therefore be necessary to carry out measurements (which should be simultaneous if a transfer function is required) at several positions to record maximum vibration magnitudes. When the building is higher than four floors (approximately 12 m) additional measuring points should be added every four floors and at the top of the building. When the building is more than 10 m long, the measuring positions should be selected at a horizontal spacing not exceeding 10 m. Measurements should be made on the side of the building facing the source.

When the purpose is to evaluate human exposure to vibration in the building, or to assess the effect of vibration on sensitive equipment within the building, measurements should be taken on the structural surface supporting the human body or the sensitive equipment.

When ground vibration sources are being considered, it is usual to orientate the transducers with respect to the radial direction, defined as the line joining the source to the transducer.

When studying structural response to ground vibration, it is more usual to orientate transducers with respect to the major and minor axes of the building structure.

If it is not possible to make measurements at the foundation, transducers should be well coupled to the ground.

9.2.3 Parameter to measure

With an impulsive source of vibration, it is recommended to measure the peak value attained from the beginning to the end of a drive. It is also recommended to measure in terms of PPV if the risk of damage to the building is the primary concern, and there is also an interest in human reaction. If the concern is purely for human tolerance, then weighted acceleration is the preferred parameter. In the case of sensitive equipment, it is necessary to check the environmental vibration limit data supplied by the manufacturer and select accordingly.

A survey of the sensitivity of the neighbourhood to vibration is desirable.

[A1) 9.2.4 Calibration of measuring equipment

Ideally, immediately before and after vibration measurements, the response of the whole measurement instrumentation chain should be checked. However, this is not always practicable and it is acceptable to set transducer sensitivities in measurement instruments using data provided by the manufacturer through its own calibration laboratory or by a United Kingdom Accreditation Service (UKAS) registered independent calibration laboratory, provided that a current calibration certificate traceable to national standards is available. The transducer sensitivities used should be included with the site measurement records. In addition, at certain time intervals, e.g. every 2 years, more extensive instrumentation calibration may be prescribed by authorities responsible for the use of the results.

Measurements of weighted acceleration or the derived Vibration Dose Value (VDV), should be carried out using accelerometers, in accordance with BS 6472-1 and with equipment as specified in BS EN ISO 8041:2005. (A1]

[A1) 9.2.5 (A1] Record sheets

NOTE Annex H contains examples of pro forma record sheets for site measurements and for vibration data summaries which have been devised for a multi-channel digital data acquisition system.

An important aspect of monitoring vibrations is the preparation and maintenance of records of salient details of the site observations. The format should be determined according to the circumstances appropriate to each investigation.

[A1) 9.2.6 (A1] Trial measurements

The various formulae which have been developed empirically to predict vibration levels at a receiving point do not take into account variability of ground strata, the pile-soil interaction process, coupling between the ground and the foundations, etc. Hence these formulae can only provide a first assessment of whether or not the vibrations emanating from a site are likely to constitute a problem.

More accurate assessment can be achieved by the calibration of the site, i.e. the establishment of a site-specific formula. In the case of impact pile driving, the data necessary for the derivation of the formula can be obtained from one or more trial drive(s) using a piling rig, and recording the vibration levels at various distances from the pile position.

Trial blasting should be undertaken where practicable on sites where blasting methods are to be used, to assist in the calibration of the site.

Vibration measurements may also be taken on structures to provide information on the coupling between the soil and the foundations and amplification effects within a building. A range of impact energies should be used to encompass the energy levels associated with the intended piling works.

Annex A (informative) Legislative background

A.1 Statutory controls over vibration

Citizens have a right to seek redress through common law action in the courts against the intrusion of unreasonable levels of noise or vibration which might affect their premises. In addition, there are two significant statutory remedies which enforcing authorities can employ to achieve the following two similar objectives:

a) enforcement action to prevent or secure the abatement of a statutory nuisance; and

b) use of specific national legislation to control vibration from construction sites and other similar works.

Part III of the Environmental Protection Act 1990 [10] contains the mandatory powers available to local authorities within England and Wales in respect of any vibration which either constitutes or is likely to cause a statutory nuisance. Section 79 of this Act defines statutory nuisance and places a duty on a local authority to inspect the area to detect any statutory nuisances which ought to be dealt with under Section 80. Under this section, where a local authority is satisfied of the existence, recurrence or likely occurrence of a statutory nuisance, it has to serve an abatement notice on the appropriate person or persons. Failure to comply with the terms of this notice is an offence which can result in proceedings in a Court of Summary Jurisdiction.

Section 82 of the Environmental Protection Act permits the court to act on a complaint by any person who might be aggrieved by the existence of a statutory nuisance and in these circumstances the court might follow the procedures described in the previous paragraph. Similar procedures to the above, for the control, in Scotland, of statutory nuisances caused by vibration, are found under Sections 58 and 59 of the Control of Pollution Act 1974 [9]. In Northern Ireland the relevant equivalent provisions are contained in the Pollution Control and Local Government (Northern Ireland) Order 1978 [15].

Sections 60 and 61 of the Control of Pollution Act 1974 [9] give local authorities in England, Scotland and Wales special powers for controlling vibration arising from construction and demolition works on any building or civil engineering sites. In Northern Ireland, equivalent powers are contained in the Pollution Control and Local Government (Northern Ireland) Order 1978 [15]. Powers under Sections 60 and 61 and their equivalent in Northern Ireland are confined to construction, including maintenance and repair, and to demolition works carried out on all building structures and roads. They are described in detail in **A.2.3**.

Under Part III of the Control of Pollution Act 1974 [9], Section 71 requires the Secretary of State to approve a code of practice for the execution of works which come within the scope of Section 60.

A.2 UK Acts and Regulations

A.2.1 Health and Safety at Work etc. Act 1974

The protection of employed persons is covered by the Health and Safety at Work etc. Act 1974 [16].

Section 2 of the Act requires all employers to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all their employees. Section 3 concerns employers' duties to persons not in their employment who might be exposed to health and safety risks. Section 6 requires designers, manufacturers, importers or suppliers to ensure, so far as is reasonably practicable, that articles for use at work are so designed and constructed as to be safe and without risks to health when properly used, that any necessary research to this end is carried out and that adequate information on the safe use of the articles is made available.

Section 7 places a duty on employees to take reasonable care for the health and safety of themselves and of other persons who might be affected, and to co-operate with their employers, so far as is necessary to enable any duty or requirement to be performed or complied with. In Northern Ireland, equivalent powers are contained in the Health and Safety at Work (Northern Ireland) Order 1978 [17].

A.2.2 Control of Vibration at Work Regulations 2005

The Control of Vibration at Work Regulations 2005 [2] implement Directive 2002/44/EC [18].

The regulations apply to both hand–arm vibration (HAV) and whole body vibration (WBV). The main requirements are triggered by two "action levels", one each for HAV and for WBV and two "limit levels", one each for HAV and for WBV. The values of these levels and limits are expressed in terms of daily exposure to frequency and time weighted acceleration related to 8 h of 2.5 $m{\cdot}s^{-2}$ as the exposure action level and 5.0 $m{\cdot}s^{-2}$ as the exposure limit level for HAV, and 0.5 $m{\cdot}s^{-2}$ as the exposure action level and 1.15 $m{\cdot}s^{-2}$ as the exposure limit level for WBV (Regulation 4).

Regulation 5 imposes a duty on the employer to carry out risk assessments in the work place. Regulation 6 requires the employer to control or reduce the risk of exposure to vibration. Regulation 7 requires the employer to conduct health surveillance, where the risk assessment indicates that there is potential for harm to the employee, and requires the employee to cooperate with health surveillance. Regulation 8 relates to the implementation of a suitable programme of information and training on the hazards of exposure to mechanical vibration.

NOTE These Regulations were made under the Health and Safety at Work etc. Act 1974 [16].

A.2.3 Control of Pollution Act 1974 and Environmental Protection Act 1990

A.2.3.1 General

The Control of Pollution Act 1974 [9] and the Environmental Protection Act 1990 [10] give local authorities powers for controlling vibration from construction sites and other similar works. These powers can be exercised either before works start or after they have started. In Northern Ireland, similar provision is made in the Pollution Control and Local Government (Northern Ireland) Order 1978 [15]. Under the 1974 Act, contractors, or persons arranging for works to be carried out, also have the opportunity to take the initiative and ask local authorities to make their vibration control requirements known. Because of an emphasis upon answering vibration questions before work starts, implications exist for traditional tender and contract procedures (see **A.2.3.4**).

The procedures available under the Control of Pollution Act 1974 [9] for the control of construction vibration are illustrated in the flow diagram shown in Figure A.1.

A.2.3.2 Notice under Section 60 of the Control of Pollution Act 1974

Section 60 of the Control of Pollution Act 1974 [9] enables a local authority, in whose area work is going to be carried out, or is being carried out, to serve a notice of its requirements for the control of site noise on the person who appears to the local authority to be carrying out the works and on such other persons appearing to the local authority to be responsible for, or to have control over, the carrying out of the works.

This notice can perform the following functions.

a) Specify the plant or machinery that is or is not to be used. However, before specifying any particular methods or plant or machinery, the local authority has to consider the desirability, in the interests of the recipient of the notice in question, of specifying other methods or plant or machinery that will be substantially as effective in minimizing noise and vibration and that will be more acceptable to the recipient.

b) Specify the hours during which the construction work can be carried out.

c) Specify the level of noise and vibration that can be emitted from the premises in question or at any specified point on those premises or that can be emitted during the specified hours.

d) Provide for any change of circumstances. An example of such a provision might be that if ground conditions change and do not allow the present method of working to be continued then alternative methods of working should be discussed with the local authority.

In serving such a notice, a local authority takes account of the following:

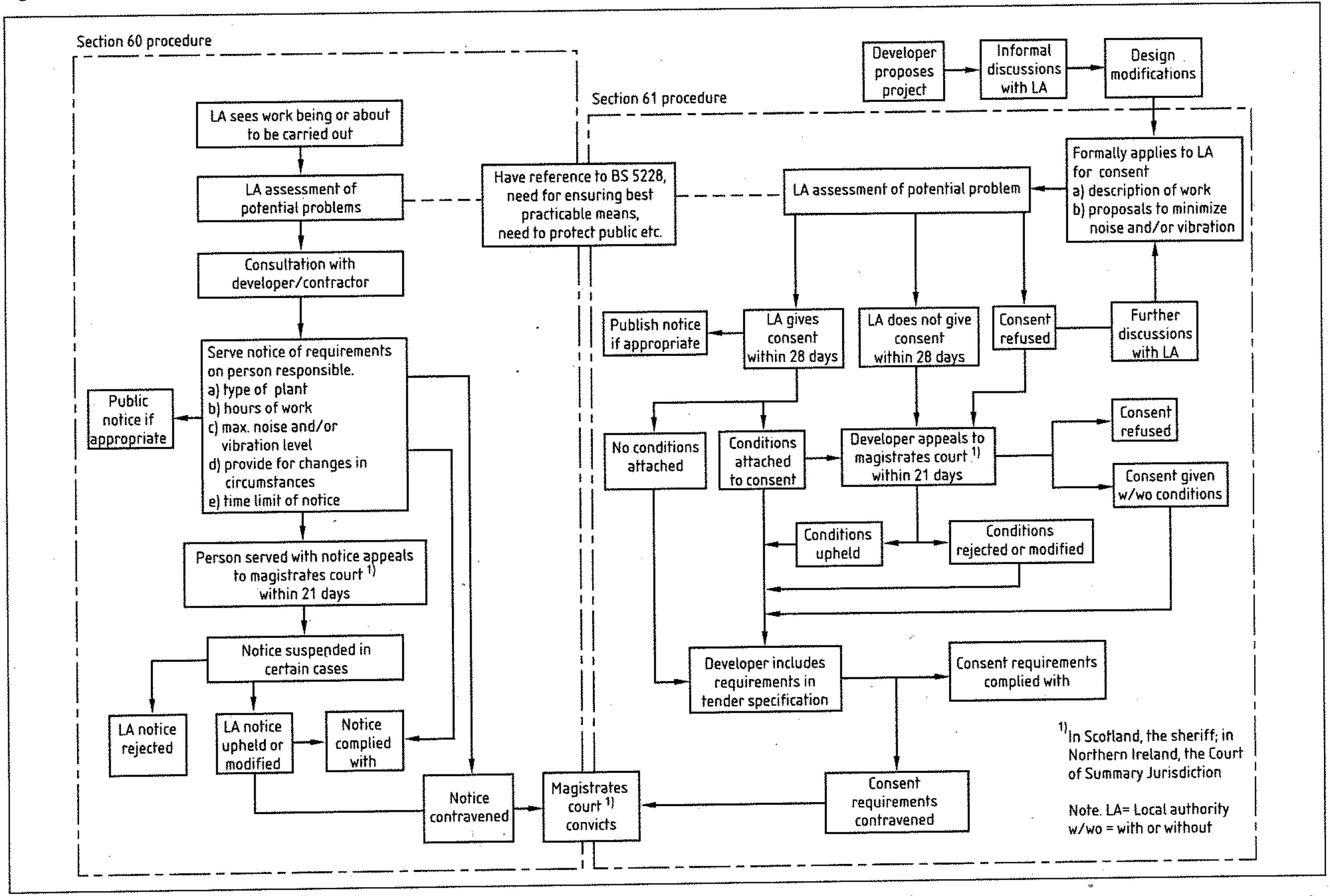
1) the relevant provisions of any code of practice issued and/or approved under Part III of the Control of Pollution Act 1974 [9];

2) the need for ensuring that the best practicable means are employed to minimize noise and vibration. "Best practicable means" recognizes that there are technical and financial limits on action that might reasonably be required to abate a nuisance;

3) other methods, plant or machinery that might be equally effective in minimizing noise and vibration, and be more acceptable to the recipient of the notice;

4) the need to protect people in the neighbourhood of the site from the effects of noise and vibration.

Figure A.1 **Procedures to control construction vibration under the Control of Pollution Act 1974**



A person served with such a notice can appeal to a magistrates court or, in Scotland, a Sheriff or, in Northern Ireland, a Court of Summary Jurisdiction, within 21 days from the date of serving of the notice. Normally the notice is not suspended pending an appeal unless it requires some expenditure on works and/or the noise or vibration in question arises or would arise in the course of the performance of a duty imposed by law on the appellant. The regulations governing appeals also give local authorities discretion not to suspend a notice even when one or other of these conditions is met, if the noise is injurious to health, or is of such limited duration that a suspension would render the notice of no practical effect; or if the expenditure necessary on works is trivial compared to the public benefit expected. The regulations governing appeals are:

- the Control of Noise (Appeals) Regulations 1975 [19];
- the Statutory Nuisance (Appeals) Regulations 1990 [20] as amended;
- in Northern Ireland, the Control of Noise (Appeals) Regulations (Northern Ireland) 1978 [21];
- in Scotland, the Control of Noise (Appeals) (Scotland) Regulations 1983 [22]).

A.2.3.3 Consents under Section 61 of the Control of Pollution Act 1974

Section 61 of the Control of Pollution Act 1974 [9] concerns the procedure adopted when a contractor (or developer) takes the initiative and approaches the local authority to ascertain its noise and vibration requirements before construction work starts. (See also **A.2.3.2**.)

It is not mandatory for applications for consents to be made, but it will often be in the interest of a contractor or an employer or their agents to apply for a consent, because once a consent has been granted, a local authority cannot take action under Section 60 of the Control of Pollution Act 1974 [9] or Section 80 of the Environmental Protection Act 1990 [10], so long as the consent remains in force and the contractor complies with its terms. Compliance with a consent does not, however, mean that nuisance action cannot be taken under Section 82 of the Environmental Protection Act 1990 or under common law. A consent can be used as a defence in appeals against an abatement notice [Statutory Nuisance (Appeals) Regulations 1990 [20] as amended].

An application for a consent has to be made at the same time as, or later than, any request for approval under the Building Regulations 2000 [23], the Building Standards (Scotland) Regulations 1990 [24] or the Building Regulations (Northern Ireland) 2000 [25], or for a warrant under Section 6 of the Building (Scotland) Act 2003 [26], when this is relevant. Subject to this constraint, there are obvious advantages in making any application at the earliest possible date. There might be advantages in having informal discussions before formal applications are made.

An applicant for a consent is expected to give the local authority as much detail as possible about the works to which the application relates and about the method or methods by which the work is to be carried out. Information also has to be given about the steps that will be taken to minimize noise and vibration resulting from the works.

Provided that a local authority is satisfied that proposals (accompanying an application) for minimizing noise and vibration are adequate, it will give its consent to the application. It can, however, attach conditions to the consent, or limit or qualify the consent, to allow for any change in circumstances and to limit the duration of the consent. If a local authority fails to give its consent within 28 days of an application being lodged, or if it attaches any conditions or qualification to the consent that are considered unnecessary or unreasonable, the applicant concerned can appeal to a magistrates court within 21 days from the end of that period.

When a consent has been given and the construction work is to be carried out by a person other than the applicant for the consent, applicant is required to take all reasonable steps to bring the terms of consent to the notice of that other person; failure to observe the terms of a consent is deemed to be an offence under the Control of Pollution Act 1974 [9].

Section 61 also requires provision to be made for emergencies.

A.2.3.4 Contractual procedures

It is likely to be to the advantage of a developer or contractor, or an employer or its agent, who intends to carry out construction or demolition work, to take the initiative and apply to the local authority for consents under the Control of Pollution Act 1974 [9].

An employer or its agent can choose to place the responsibility on the contractor to secure the necessary consents and can impose this requirement through formal contractual arrangements.

This could have implications for traditional tender and contract procedures because the local authority's noise and vibration requirements (in addition to any separate requirements defined by the employer) can be ill-defined at tendering and contract award stage. In these circumstances, any tendering contractor needs to endeavour to identify, quantify and accommodate the level of risk (in terms of both construction methodology and cost) prior to participating in the tendering process.

When a person for whom construction work is to be carried out has already sought and obtained consent from the local authority, the local authority's requirements need to be incorporated in the tender documents so that tenderers are aware of any apparent constraints arising from the consent.

A.2.4 Land Compensation Act 1973 (as amended), Highways Act 1980, Land Compensation, (Scotland) Act 1973, Land Acquisition and Compensation (Northern Ireland) Order 1973

The Noise Insulation Regulations 1975 [27], Noise Insulation (Scotland) Regulations 1975 [28] and Noise Insulation (Northern Ireland) Regulations 1995 [29] made under the powers contained respectively in the Land Compensation Act 1973 [30], the Land Compensation (Scotland) Act 1973 [31] and the Land Acquisition and Compensation (Northern Ireland) Order 1973 [32], allow a highway authority to provide insulation for dwellings and other buildings used for residential purposes by means of secondary glazing and special ventilation when highway works are expected to cause serious noise effects for a substantial period of time. The 1973 Acts also contain provisions that enable a highway authority to pay the reasonable expenses of residents who, with the agreement of the authority, have to find suitable alternative accommodation for the period during which construction work makes continued occupation of an adjacent dwelling impracticable.

The Highways Act 1980 [33] and the Land Compensation (Scotland) Act 1973 [31] enable highway authorities to acquire land by agreement when its enjoyment is seriously affected by works of highway construction or improvement. In addition, these Acts give the highway authority power to carry out works, e.g. the installation of noise barriers, to mitigate the adverse effects of works of construction or improvement on the surroundings of a highway.

A.2.5 The Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1995

The Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1995 [34] give a discretionary power to railway authorities to provide insulation or grant for insulation where noise from the construction of a new or altered railway is expected seriously to affect residential and other buildings for a substantial time.

A.2.6 Other relevant UK legislation

A.2.6.1 Surface coal extraction by opencast methods

[A1⟩ *Text deleted* ⟨A1]

[A1⟩ Opencast coal mining is governed by a wide variety of legislative instruments. ⟨A1] The legislative framework consists of several elements, the most important of which is the Coal Industry Act 1994 [37]. Other key legislation includes the Coal Industry Nationalisation Act 1946 [38], the Opencast Coal Act 1958 [39], the Town and Country Planning Act 1990 [40] and the Planning and Compulsory Purchase Act 2004 [41].

Before 1984 the British Coal Corporation's sites were authorized by the Secretary of State for Energy. Since then for all opencast sites a planning permission has been required from the appropriate Mineral Planning Authority (MPA) or, on appeal or in respect of a call-in, from the Secretary of State for Communities and Local Government in England or the Scottish Minister for Scotland or the Minister for Environment, Planning and Countryside for Wales as appropriate.

Before making a planning application, the operator often undertakes extensive drilling and other explorations to prove the coal reserves. These operations are now governed by Clause 18 of the Town and Country Planning (General Development Procedure) Order 1995 [42].

Coal operators also require a licence from the Coal Authority if they wish to explore for coal.

NOTE Almost all coal in Great Britain is vested in the Coal Authority, a non-departmental public body created by the Coal Industry Act 1994 [37]. The authority is responsible for managing the non-operational aspects of the UK coal industry.

Since July 1988 almost all the British Coal Corporation's site applications and many larger sites applied for by other operators have been accompanied by an Environmental Statement. These are required under the Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations 1999 [43]. The Environmental Statement examines the environmental implications of the proposed operations (noise, dust, visual impact, traffic, etc.) on the local community as well as the impact on the ecology and landscape of the site.

The MPA considers the application and, if satisfied that the proposals are acceptable in planning and environmental terms, approves it subject to conditions governing the site operations and restoration.

If the planning application is refused or not determined by the MPA, the operator can appeal to the Secretary of State for Communities and Local Government in England, the Minister for Environment, Planning and Countryside in Wales, or the Scottish Minister in Scotland, as appropriate. A public inquiry is held under an Inspector, and following the Inspector's report the Secretary of State in England or relevant Minister in Wales or Scotland, as appropriate, grants or refuses permission.

After an opencast site receives planning permission, an authorization from the local authority is also needed for the coal loading operations, which are Part B processes in accordance with the Regulations under Part I of the Environmental Protection Act 1990 [10].

All future coal mining operations will require a lease and licence from the Coal Authority under Part II of the Coal Industry Act 1994 [37]. Sites licensed by the British Coal Corporation before 31 October 1994 under Section 36 (2) of the Coal Industry Nationalisation Act 1946 [38] (as amended by the Coal Industry Act 1994), can, however, continue operations during the validity of those licences. Sites contained in the 1994 privatization packages have licences granted by the Government.

The previous limitation of 250 000 t on the amount of coal extracted from any one licensed opencast site was removed by the Coal Industry Act 1994.

Applicants for licences are responsible for securing the planning permission and other consents needed to work the coal, including rights to occupy the land and to disturb other minerals. Many opencast sites win significant quantities of other minerals, principally seams of fireclay beneath the coal seams. These operations also require planning permission.

A.2.6.2 Surface mineral extraction (except coal) sites

The principal legislation controlling the use of land for surface mineral extraction in Great Britain is provided by the Town and Country Planning Act 1990 [40] and the Town and Country Planning (Scotland) Act 1972 [44], both of which have been amended by the Planning and Compensation Act 1991 [45].

The primary planning legislation in Northern Ireland is the Planning (Northern Ireland) Order 1991 [46]. Acts of Parliament, rules and orders which are of relevance include the Environment Act 1995 [47] and the Planning and Compulsory Purchase Act 2004 [41]. There is also separate legislation controlling pollution, waste and statutory nuisance, much of which is now contained in the Environmental Protection Act 1990 [10].

The relevant planning authorities are as follows:

a) England: county councils, metropolitan borough councils, unitary authorities, the national park authorities and the broads authority, where appropriate;

b) Wales: the unitary planning authorities and national park planning boards where appropriate;

c) Scotland: the local authority;

d) Northern Ireland: Department of the Environment for Northern Ireland.

In England, the Secretary of State for Communities and Local Government is responsible for setting out government policy on mineral extraction. [A1) This is contained in the Minerals section of the suite of web based documents that form the Planning Practice Guidance [13]. (A1]

In Wales, general policy is supplemented by Welsh Office guidance. Policy guidance in Scotland is provided by the Scottish Office in National Planning Policy Guidelines (NPPGs) and circulars, and advice on best practice in Planning Advice Notes (PANs). NPPG 4 [49] and PAN 50 [50] are of particular relevance to this standard. The Secretary of State for Communities and Local Government in England, the Scottish Minister for Scotland, and the Minister for Environment, Planning and Countryside in Wales, all have powers as defined by the legislation in relation to the submission of planning applications, determination of appeals and in respect of development plans.

Most minerals in Britain are privately owned and are worked by commercial operating companies. Sometimes, however, ownership of the land is divorced from the rights to extract the mineral. Mineral extraction, as a form of development, requires planning permission in order to be undertaken. [A1) *Text deleted* (A1] The Mineral Planning Authorities (MPAs), or on appeal the Secretary of State, will consider and either approve or refuse mineral planning applications according to their decision as to the acceptability of the proposals. In the case of an appeal, a public inquiry might be held and the Inspector (Reporter in Scotland) might determine the appeal or make a recommendation to the Secretary of State. All planning permissions are subject to conditions controlling relevant aspects of the development, including noise and vibration.

A.3 Local authorities

The local authorities exercising powers under Part III of the Control of Pollution Act 1974 [9] and Part III of the Environmental Protection Act 1990 [10] are as follows:

a) in England, the council of a district or a district or a London borough, the Common Council of the City of London, the Sub-Treasurer of the Inner Temple and the Under Treasurer of the Middle Temple;

b) in Wales, the council of a county or a county borough;

c) in Scotland, an islands or district council.

In Northern Ireland, district councils exercise similar functions under the Pollution Control and Local Government (Northern Ireland) Order 1978 [15].

The local authorities exercising planning powers are, according to the circumstances, in England, county councils or district councils, and in Scotland, the regional councils in the Borders, Highland, and Dumfries and Galloway Regions and district or islands councils elsewhere. In Northern Ireland, planning control is a function of the Department of the Environment (Northern Ireland).

For the winning and working of minerals, the relevant authority needs to be consulted as follows:

- England: county councils, metropolitan boroughs, unitary authorities and national park planning boards where appropriate;
- Wales: the unitary planning authorities and national park planning boards where appropriate;
- Scotland: unitary planning authorities;
- Northern Ireland: Department of the Environment for Northern Ireland.

In the case of uncertainty as to which local authority or local authority department to consult about a vibration problem, a good starting point is often the environmental health department of the district or London borough council; in Scotland, the district or islands council; or in Northern Ireland, the Department of Environment (Northern Ireland) in Belfast.

Annex B (normative) Significance of vibration effects

B.1 Criteria for the assessment of the significance of vibration effects

Construction vibration assessments are generally undertaken for three main reasons:

a) *For Environmental Impact Assessments (EIAs).* Most major developments now need to be assessed in accordance with the Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations 1999 [43]. This is where the development might result in significant effects upon the environment. Therefore, criteria are needed to allow these assessments to be undertaken.

b) *Assessments for developments that do not require EIA.* Construction vibration assessments are sometimes required by developers to advise on the likely effects that might arise and appropriate actions that might need to be taken to minimize effects.

c) *Control of Pollution Act (CoPA) 1974 [9], Section 61, "Applications for prior consent for work on construction sites".* Applications under this section of the CoPA are often found to be desirable and useful by both the local authority and the contractor. The applications would usually include (as identified in the CoPA):

   1) details of the works and the method by which they are to be carried out; and

   2) the steps proposed to be taken to minimize vibration resulting from the works.

By gaining consent under Section 61, the contractor gains protection from action under Section 60 of the CoPA, whereby a stop or enforcement notice cannot be served on the contractor, as long as the works are carried out in accordance with the details in the application.

This annex describes methods to identify the likely significance of vibration levels from construction and demolition activity. Further advice on the significance of vibration is given in [A1) BS 6472, BS 7385-2 and BS ISO 4866:2010 (A1].

B.2 Human response to vibration

Human beings are known to be very sensitive to vibration, the threshold of perception being typically in the PPV range of 0.14 $mm{\cdot}s^{-1}$ to 0.3 $mm{\cdot}s^{-1}$. [A1) As vibrations increase above these values they can (A1] disturb, startle, cause annoyance or interfere with work activities. At higher levels they can be described as unpleasant or even painful. In residential accommodation, vibrations can promote anxiety lest some structural mishap might occur. Guidance on the effects on physical health of vibration at sustained high levels is given in BS 6841, although such levels are unlikely to be encountered as a result of construction and demolition activities.

BS 6472 sets down vibration levels at which minimal adverse comment is likely to be provoked from the occupants of the premises being subjected to vibration. It is not concerned primarily with short-term health hazards or working efficiency. It points out that human response to vibration varies quantitatively according to the direction in which it is perceived. Thus, generally, vertical vibrations are more perceptible than horizontal vibrations, although at very low frequencies this tendency is reversed.

A kindred problem is that vibrations can cause structure-borne noise which can be an additional irritant to occupants of buildings. Loose fittings are prone to rattle and movement.

BS 6472, as stated, provides guidance on human response to vibration in buildings. Whilst the assessment of the response to vibration in BS 6472 is based on the VDV and weighted acceleration, for construction it is considered more appropriate to provide guidance in terms of the PPV, since this parameter is likely to be more routinely measured based upon the more usual concern over potential building damage. Furthermore, since many of the empirical vibration predictors yield a result in terms of PPV, it is necessary to understand what the consequences might be of any predicted levels in terms of human perception and disturbance. Some guidance is given in Table B.1.

Table B.1 **Guidance on effects of vibration levels**

Vibration level A), B), C)	Effect
0.14 mm·s^{-1}	Vibration might be just perceptible in the most sensitive situations for most vibration frequences associated with construction. At lower frequencies, people are less sensitive to vibration.
0.3 mm·s^{-1}	Vibration might be just perceptible in residential environments.
1.0 mm·s^{-1}	It is likely that vibration of this level in residential environments will cause complaint, but can be tolerated if prior warning and explanation has been given to residents.
10 mm·s^{-1}	Vibration is likely to be intolerable for any more than a very brief exposure to this level [A1] in most building environments [A1].

[A1]

A) The magnitudes of the values presented apply to a measurement position that is representative of the point of entry into the recipient.

B) A transfer function (which relates an external level to an internal level) needs to be applied if only external measurements are available.

C) Single or infrequent occurrences of these levels do not necessarily correspond to the stated effect in every case. The values are provided to give an initial indication of potential effects, and where these values are routinely measured or expected then an assessment in accordance with BS 6472-1 or -2, and/or other available guidance, might be appropriate to determine whether the time varying exposure is likely to give rise to any degree of adverse comment. [A1]

B.3 Structural response to vibration

B.3.1 General

NOTE 1 Refer for example to R.J. Steffens' Structural vibration and damage [53], CIRIA Technical Note 142 [54] or BRE Digest 403 [55]; there is also a useful list of references at the end of BS 7385-2.

Extensive studies carried out in the UK and overseas (see Note 1) have shown that documented proof of actual damage to structures or their finishes resulting solely from well-controlled construction and demolition vibrations is rare. There are many other mechanisms which cause damage, especially in decorative finishes, and it is often incorrectly concluded that vibrations from construction and demolition sites are to blame.

NOTE 2 It has been suggested that vibrations generally provide one trigger mechanism which could result in the propagation of an incipient failure of some component which hitherto had been in a metastable state.

NOTE 3 Vibration can increase the density of and cause settlement in loose, wet and cohesionless soils, which can put structures at risk.

In some circumstances, however, it is possible for the vibrations to be sufficiently intense to promote minor damage. Typically this damage could be described as cosmetic and would amount to the initiation or extension of cracks in plasterwork, etc., rather than the onset of structural distress. In more severe cases, falls of plaster or loose roof tiles or chimney pots can occur.

Assessing the vulnerability or otherwise of building structures to vibration-induced damage needs rather more detailed structural knowledge at the outset than is generally available. Among the points that should be taken into account are the following:

a) the design of the structure;

b) the nature, condition and adequacy of the foundations and the properties of the ground supporting these;

c) the age of the structure;

d) the method and quality of construction, including finishes;

e) the general condition of the structure and its finishes;

f) a schedule of existing defects, especially cracks, supplemented where necessary by a photographic record;

g) any information pertaining to major alterations, such as extensions, or past repair work;

h) the location and level of the structure relative to the construction or demolition works;

i) the natural frequencies of structural elements and components;

j) the duration of construction and demolition activities.

B.3.2 Response limits of buildings

The response of a building to groundborne vibration is affected by the type of foundation, underlying ground conditions, the building construction and the state of repair of the building.

[A1⟩ BS 7385-2 and BS ISO 4866:2010 provide ⟨A1] guidance on vibration measurement, data analysis and reporting as well as building classification and guide values for building damage. Extracts are provided below.

The damage threshold criteria presented in BS 7385-2 are based upon systematic studies using a carefully controlled vibration source in the vicinity of buildings. Strains imposed in a building by ground motion will tend to be greater if lower frequencies predominate. The relative displacements associated with cracking will be reached at higher vibration magnitudes with higher frequency vibration. BS 7385-2 provides frequency dependent threshold levels which are judged to give a minimal risk of vibration-induced damage.

The dominant frequency to use for the assessment is that associated with the greatest amplitude. If the building vibration is multi-frequency in nature, then frequencies should be determined from an amplitude-frequency plot, with each significant peak being examined in turn.

Limits for transient vibration, above which cosmetic damage could occur, are given numerically in Table B.2 and graphically in Figure B.1 in terms of the component PPV. 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 component PPV a maximum displacement of 0.6 mm (zero to peak) should be used.

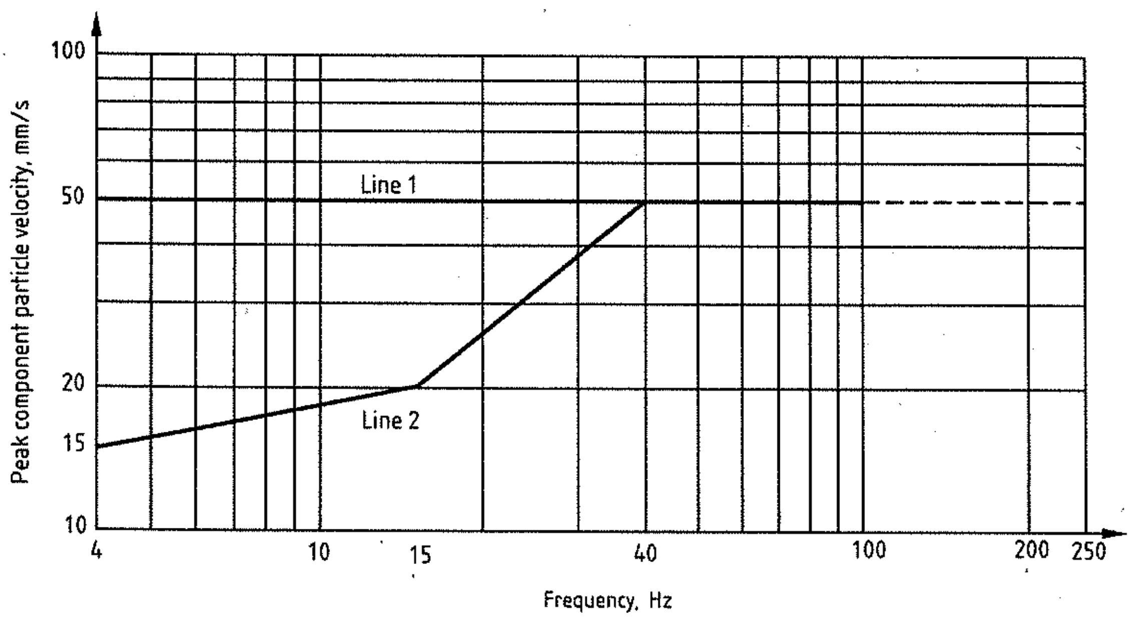
Table B.2 **Transient vibration guide values for cosmetic damage**

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

NOTE 1 Values referred to are at the base of the building.

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

Figure B.1 **Transient vibration guide values for cosmetic damage**



Minor damage is possible at vibration magnitudes which are greater than twice those given in Table B.2, and major damage to a building structure can occur at values greater than four times the tabulated values. Definitions of the damage categories are presented in [A1) BS ISO 4866:2010, **12.6** (A1].

The guide values in Table B.2 relate predominantly to transient vibration which does not give rise to resonant responses in structures, and to low-rise buildings. Where the dynamic loading caused by continuous vibration is such as to give rise to dynamic magnification due to resonance, especially at the lower frequencies where lower guide values apply, then the guide values in Table B.2 might need to be reduced by up to 50%.

BS 7385-2 notes that the probability of damage tends towards zero at 12.5 $mm \cdot s^{-1}$ peak component particle velocity.

[A1) Current experience suggests that these values may be reduced where the preliminary survey reveals existing significant defects (such as defects which are a result of settlement) of a structural nature, the amount of reduction being judged on the severity of such defects (see for example BS ISO 4866:2010, **5.5**). (A1]

Important buildings which are difficult to repair might 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.

B.4 Assessment of vulnerability of ground-related structures and services

B.4.1 General

Due to the variability of ground conditions, structures, services, sources and activities, each application should be assessed on a case-by-case basis.

Some guidance on specific issues is given in **B.4.2** to **B.4.4**.

B.4.2 Retaining walls

Unlike conventional buildings, which are tied together by crosswalls, intermediate floors and roofs, retaining walls might have little lateral restraint near their tops. This can result in substantial amplification of vibrations particularly in the horizontal mode normal to the plane of the wall. Amplification factors of between 3 and 5 are typical.

For slender and potentially sensitive masonry walls, it is recommended that threshold limits for PPV of 10 $mm \cdot s^{-1}$ at the toe and 40 $mm \cdot s^{-1}$ at the crest should generally be adopted. Propped or tied walls or mass gravity walls can be subject to values 50% to 100% greater than these limits. Similar values could be applied to well-supported steel pile and reinforced concrete retaining walls. Where walls are in poor condition, the allowable values should be diminished and at the same time additional propping or other methods of support should be devised. For continuous vibrations, all the above levels should be reduced by a factor of 1.5 to 2.5 according to individual circumstances.

B.4.3 Slopes and temporary excavations

The effect of groundborne vibrations on the stability of temporary earthworks such as modified soil slopes and open excavations should be taken into account in order to avoid risk to personnel and partially completed works from dislodged lumps of soil, local collapse of soil faces or even ground movement due to overloading and failure of temporary ground retention systems.

The risk to stability is dependent on the extent to which the factor of safety under static loading is reduced by the vibrations, and hence on the intensity, characteristics and duration of the vibration and the soil response. The possibility that inherent weaknesses might exist in the soil due to the release of stress and subsequent surface weathering should be borne in mind.

B.4.4 Underground services

Some statutory undertakers have introduced criteria governing the maximum level of vibrations to which their services should be subjected. These criteria are usually conservative and it is recommended that the following limits be used in the absence of specific criteria from the undertakers:

a) maximum PPV for intermittent or transient vibrations 30 $mm{\cdot}s^{-1}$;

b) maximum PPV for continuous vibrations 15 $mm{\cdot}s^{-1}$.

Criteria should be applied at the nearest point to the source or activity.

Even a PPV of 30 $mm{\cdot}s^{-1}$ gives rise to a dynamic stress which is equivalent to approximately 5% only of the allowable working stress in typical concrete and even less in iron or steel.

In the event of encountering elderly and dilapidated brickwork sewers, the base data should be reduced by 20% to 50%. For most metal and reinforced concrete service pipes, however, the values in a) and b) are expected to be quite tolerable. There is often some difficulty in assessing the true condition of underground pipes, culverts and sewers. Among the factors which could mean that such services are in a state of incipient failure are poorly formed joints, hard spots, badly prepared trench bases, distortion due to settlement or heave, or unstable surrounding ground caused by previous or existing leaks.

B.5 Assessment of vulnerability of contents of buildings

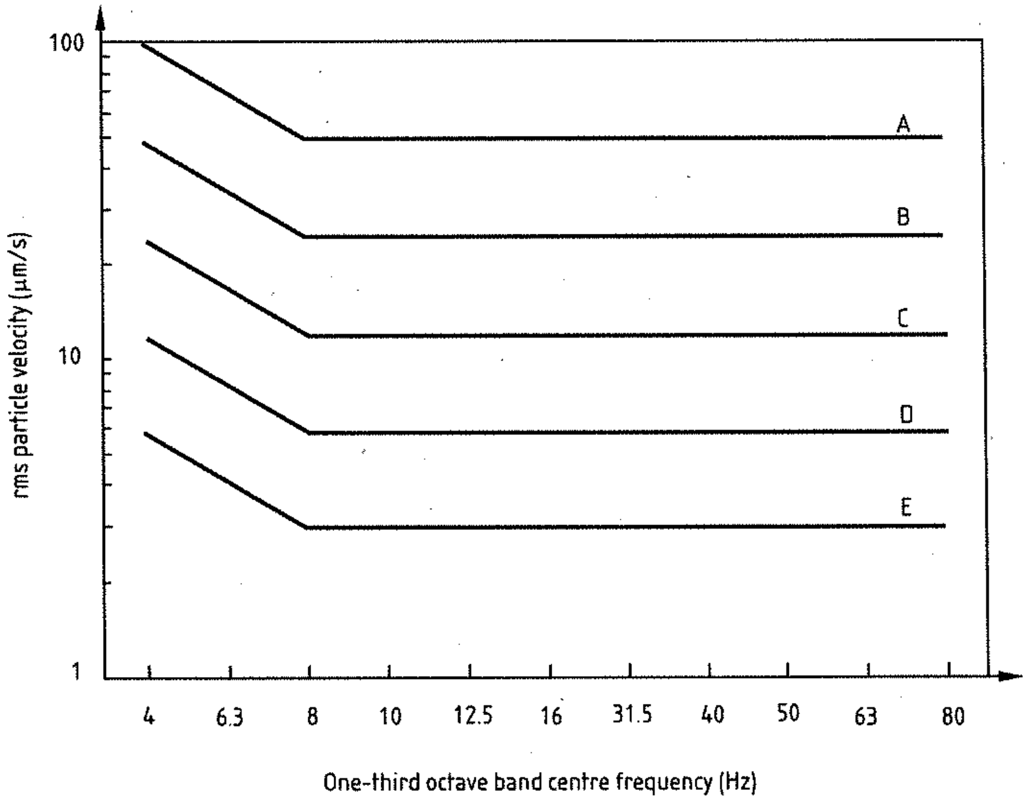
Many types of equipment, activities and processes are sensitive to vibration, often at levels of vibration below those that are directly perceptible to people. These include hospital operating theatres (especially those where microsurgery is undertaken), scientific laboratories and a range of industrial processes, such as optical typesetting, microelectronics manufacturing and automatic letter sorting. In electrical power generation, turbine shafts are not able to accommodate large oscillatory displacements.

Where there is uncertainty concerning the level of transmitted vibration and its acceptability to the particular environment, it is advisable to investigate the actual conditions and requirements in detail. Preliminary trials and monitoring can then be designed to establish a suitable procedure for the work. Alternatively, vibration criteria can be established through discussion with the manufacturer, supplier or operator. Where case-specific information is not available, or if otherwise appropriate, reference may be made to information from other sources, such as previous experience or published information. Figure B.2 illustrates a suite of curves showing the sensitivity to vibration of a variety of equipment, taken from reference [56].

Although modern electrical installations incorporate solid state electronics, any disc drive units can be vulnerable to excessive vibration or shock. Major manufacturers have set acceptable external vibration criteria for their equipment, in both operating and transit modes. Criteria are often expressed in terms of limits on vibratory displacement up to a certain frequency and limits on vibratory acceleration at higher frequencies. A sinusoidal relationship is given between these parameters which can therefore be used to calculate the corresponding particle velocities. For continuous vibrations, the allowable thresholds are typically set at about 40% of the permitted levels of intermittent vibrations.

Guidance in relation to telephone exchanges is given in ETS 300 019.

Figure B.2 **Example of vibration criteria**



NOTE For key to graph, see Table B.3.

Table B.3 **Key to vibration criteria illustrated in Figure B.2**

Curve (from Figure B.2)	Facility, equipment or use	rms vibration velocity μm/s
A	Bench microscopes at up to 400× magnification; optical and other precision balances; coordinate measuring machines; metrology laboratories; optical comparators. Microelectronics manufacturing equipment – Class A: Inspection, probe test, and other manufacturing support equipment.	50
B	Micro surgery, eye surgery, neurosurgery; bench microscopes at magnification greater than 400×; optical equipment on isolation tables. Microelectronics manufacturing equipment – Class B: aligners, steppers, and other critical equipment for photolithography with line widths of 3 μm or more.	25
C	Electron microscopes at up to 30 000× magnification; microtomes; magnetic resonance imagers. Microelectronics manufacturing equipment – Class C: aligners, steppers, and other critical equipment for photolithography with line widths of 1 μm.	12
D	Electron microscopes at greater than 30 000× magnification; mass spectrometers; cell implant equipment. Microelectronics manufacturing equipment – Class D: aligners, steppers, and other critical equipment for photolithography with line widths of 0.5 μm; includes electron-beam systems.	6
E	Microelectronics manufacturing equipment – Class E: aligners, steppers, and other critical equipment for photolithography with line widths of 0.25 μm; includes electron-beam systems; un-isolated laser and optical research systems.	3

Annex C (informative) Measured vibration levels for piling (current data)

Table C.1 contains recently acquired information on piling and ancillary operations, supplied by the Federation of Piling Specialists and the Steel Piling Group. A set of historic data tables taken from the 1992 edition of BS 5228-4 is given in Annex D.

Table C.1 **Summary of case history data on vibration levels**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances						
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV
						m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$
1	2000 New Orleans (USA) [57]	Very soft to soft clay 0 m to 10 m, soft to medium stiff clay 10 m to 20 m	U-shaped LX-16 sheet piles	Pressed-in steel sheet piles	N/R	4.8	2.5 to 4.3	24	< 0.5		
2	1992 Utrecht (Netherlands) [57]	—	U-shaped sheet piles	Pressed-in steel sheet piles	N/R	7.1	0.3 to 0.7				
3	2006 Blackpool	Made ground 0 m to 3 m, loose to very dense sand and silt 3 m to 17 m, firm to stiff clay 17 m to 25 m	244 mm diameter, 13.2 mm wall thickness, 11.5 m to 20 m long	Driven steel tubular piles	Estimated as 9810 J	5	12.32 to 13.91	10	8.45 to 8.76	20	4.32 to 5.4
4	2006 Blackpool	Made ground 0 m to 3 m, loose to very dense sand and silt 3 m to 17 m, firm to stiff clay 17 m to 25 m	275 mm square, 9 m to 10.2 m long	Driven precast concrete square piles	Estimated as 9810 J	5	10.16 to 11.4	10	6.41	20	4.32 to 5.6

Annex D (informative) Measured vibration levels for piling (historic data)

D.1 General

The data given in this annex is largely historical, and is taken unaltered from the tables originally given in BS 5228-4:1992. More recent data is given in Annex C.

Information on measured vibration levels arising from various forms of piling and kindred operations is summarized in Table D.1 to Table D.11. Data have been compiled from case histories recorded throughout the UK. Examination of the tabulated results will indicate the magnitude of scatter that can be anticipated.

D.2 Symbols and abbreviations used in Table D.1 to Table D.11

For the purposes of Table D.1 to D.11, the following symbols and abbreviations apply.

Ref no.	Where the reference is unprefixed, this represents a case history associated with an actual site. Where investigations yielded inadequate (or no) measurements, they have been omitted. Where the reference number is prefixed by "C", this represents a case history contributed to the CIRIA project RP299. The project report is CIRIA Technical Note 142 [54]. Only case histories reporting measured vibration levels with relevant distances and some geographical information are included in the table. Where the reference number is prefixed by "M", this represents a case history which does not fall into either of the above two categories.
♦ §	Indicates that some annoyance (human perception of vibration) was reported.
N/R	Not recorded or not reported
V	Vertical
H	Horizontal
P	Penetration phase } for vibroflotation/vibroreplacement
C	Compaction of stone column phase } for vibroflotation/vibroreplacement
PPV	Where peak particle velocities are quoted the values will normally be resultant or substitute resultant values (i.e. vectorial sums of the three orthogonal components) unless indicated to the contrary
*	Indicates that the PPV shown has been calculated from measured displacement and frequency of vibration
+	Indicates that the PPV shown has been calculated from measured acceleration and frequency of vibration
91	See explanation in appropriate "Remarks" entry
[A1] ϕ	Pile diameter [A1]

Table D.1 **Summary of historic case history data on vibration levels measured during impact bored piling (tripod)**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
1	1971 London EC2	Made ground/ gravel/ London clay	Depth 12 m	Boring	N/R	0.9	3.9*	2.4	1.6*	3.7	1.1*	Measured on ground next to 17th century church
2	1972 London SW1	Made ground/ soft clay/ballast/ London clay	500 mm ϕ depth N/R	Driving casing	N/R	2	3.3*	6	1.8*	6	0.5*	Horizontal radial measurements
			600 mm ϕ depth N/R	Base ramming gravel		1.5	6.2*	3	1.9*			
3	1973 London EC2	Made ground/peat/ gravel/London clay	500 mm ϕ 20 m depth	Driving casing	N/R	2.5	2.8					Measured on 17th century church
4 ♦	1974 Dundalk (Louth)	Soft silts/gravels/ boulders	N/R	Driving casing	N/R	1.5	2.4					Cracking of adjacent property owing to loss of ground prior to piling
5 ♦	1980 Luton (Beds)	Ballast/chalk	600 mm ϕ 8.5 m depth	Initial boring	N/R	10	0.7					Shored retaining wall in poor condition
6	1980 York (N. Yorks)	Rubble with obstructions/soft silty clay/stiff clay	450 mm ϕ 10.5 m depth	Boring	N/R	1	8	2.5	4	8	2	Adjacent structures elderly with existing cracks
				Driving casing	N/R	1.2	4					
				Driving casing against obstruction	N/R	1.2	16					
7 ♦	1981 Berwick-upon-Tweed (Northumber-land)	Tarmac/soft sandy/ silty clay/sandstone bedrock	450 mm ϕ	Boring through tarmac	N/R	6	6.5	20	0.7			Vertical 4 $mm \cdot s^{-1}$ at 6 m
			4 m to 8 m depth	Boring obstruction (boulder)	N/R	6	4.25					Vertical component only measured

Table D.1 **Summary of historic case history data on vibration levels measured during impact bored piling (tripod)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
8	1982 Stockton-on-Tees (Cleveland)	Fill including timbers/sand/ boulder clay	450 mm ϕ 13 m to 18 m depth	Driving casing	N/R	2.5	8	3.5	4	8	2	Old buildings (one listed) adjacent to site
				Boring through obstruction	N/R	4	8	6.5	4	11	2	
9	1982 London SW1	Fill/sandy silt/wet ballast/London clay below 9 m	600 mm ϕ 12 m depth	Boring	N/R	1.5	2.2					Near to a telephone exchange Trial borings (pre-contract)
10	1982 Bristol (Avon)	Soft silts overlying sandstone	500 mm ϕ and 600 mm ϕ 3 m to 12 m depth according to rockhead.	Boring	N/R	4.5	8	7	2.7	12	1.8	Medieval listed buildings adjacent to site
				Chiselling	N/R	4.5	12	10	7	12	3	
				Driving casing	N/R	4.5	4			12	2.5	
			1.5 m penetration rock sockets	Boring	N/R	4.5	2.6	7.5	2.1			After pre-drilling rock
				Chiselling	N/R	4.5	6.5	8	1.7			
11	1982 Halifax (W. Yorks)	Loose rock fill over weathered rock over rock	500 mm ϕ 15 m to 17 m depth	Boring	N/R	10	0.8	25	0.65	48	0.45	Sensitive industrial process in adjacent building
				Base ramming	N/R	10	1.5	15	1.3	30	1.2	
				Rockfill								
12	1983 Swansea (W. Glamorgan)	Made ground/ dense sands and gravels with cobbles and boulders	500 mm ϕ 4.5 m depth	Driving casing	N/R	1	10	10	0.85			Measured on adjacent comercial building
				Boring	N/R	1	9.8	11	0.75			
				Driving casing	N/R	7	6.4	11	1.5			Measured on road surface above 19th century sewer
				Boring	N/R	7	6.6	14	1.4			

Table D.1 **Summary of historic case history data on vibration levels measured during impact bored piling (tripod)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
13	1983 Lincoln (Lincs)	Backfilled quarry-grouted stiff sandy clay and limestone blocks/ lias clay below 6 m	500 mm ϕ 12 m to 15 m depth	Base ramming	N/R	4.5	22.2	20	1.6			
				Initial boring	N/R	4.5	12.4	20	0.73			
				Driving casing	N/R	4.5	3.3	20	0.41			
				Clay boring	N/R	4.5	0.75	20	0.16			
14	1983 London EC3	Backfilled sand/ soft sandy soil/ ballast becoming dense with stones/ London clay below 8.7 m	600 mm ϕ 23 m to 25 m depth	Boring (obstruction)	N/R	0.7	9.5	5	3.7			Measured on retained facades
				Boring (stones)	N/R	8	8.9					
				Driving casing	N/R	0.7	11.5	5	4.5	8[91]	4.9[91]	Different pile position
15	1984 Guildford (Surrey)	Surface crust/very soft clay/sands and gravels/clay Clay horizon between 5 m and 8.5 m	450 mm ϕ 12.5 m depth	Initial boring through crust	N/R	2.5	10.4	3.5	12.3	7	6.5	Sensitive equipment in adjacent building (protected by cut-off trench)
				Driving casing	N/R	2.5	5.5	3.5	5.3	7	3.6	
				Boring soft clay	N/R	3.5	1.1	7	0.8			
16	1984 London EC2	Made ground/ dense ballast/ London clay below 5.5m	600 mm ϕ 22 m depth	Driving casing	N/R	3	7.1	5.5	2.3	10§	0.9§	Measured on retained façade
				Boring casing	N/R	3	4.1	5.5	1.6	10§	0.86§	
				Shaking clay out of pump	N/R	3	7.5	5.5	0.75	10§	0.45§	
				Boring brick work obstruction	N/R	6	8.6	9	2.6	13§	1.5§	

Table D.1 **Summary of historic case history data on vibration levels measured during impact bored piling (tripod)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s⁻¹	m	mm·s⁻¹	m	mm·s⁻¹	
17 ◆	1985 London EC3	Made ground/ dense ballast/ London clay below 6.5 m	500 mm ϕ 8 m depth	Driving casing 2 rigs (2nd at 10 m)	N/R	4	2.5					Trial borings Computer equipment beyond party wall

Table D.2 **Summary of historic case history data on vibration levels measured during driven cast-in-place piling (drop hammer)**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s⁻¹	m	mm·s⁻¹	m	mm·s⁻¹	
18 ◆	1981 London SE1	Made ground/peat/ Thames ballast/ London clay below 10 m	500 mm ϕ 6 m depth with enlarged base	Driving tube	N/R	20	2.7	100	0.96			Bottom-driven
				Enlarging base		20	3.6	100	1.4			
19 ◆	1982 London SW6	Fill/ballast/ London clay	500 mm ϕ 4 m to 7 m depth with enlarged base	Driving tube	N/R	30	2.3					Bottom-driven
				Expelling plug	N/R	30	2.6					
				Enlarging base	N/R	30	2.3					
20 ◆	1983 Aylesbury (Bucks)	Fill/soft material/ clay becoming stiff	450 mm ϕ 10 m depth with enlarged base	Driving tube	N/R	4	8.4	20	5.0			Bottom-driven
				Expelling plug	N/R	4	6.1	20	4.8			
				Enlarging base	N/R	4	4.0	20	4.4			
21 ◆	1983 Aldershot (Hants)	Dense fine sand	450 mm ϕ approx 6 m depth	Driving tube	58.9 kJ	120	1.0					Tube driven open ended initially to remove some sand prior to driving with shoe top-driven

Table D.2 **Summary of historic case history data on vibration levels measured during driven cast-in-place piling (drop hammer)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
22 ♦	1983 Horsham (W. Sussex)	Peaty, silty alluvia over shale and sandstone	350 mm ϕ 7.5 m to 8 m depth	Driving tube	38.8 kJ	21	2.9	28	2.7	35	2.4	Top-driven
				Extracting tube		21	3.2	28	3.9	35	3.1	
23 ♦	1983 Redhill (Surrey)	Dense fine sand with ironstone bands	450 mm ϕ 8 m depth (max) (6 m average)	Driving tube	N/R	22.5	3.1	43	1.1			Bottom-driven, computer etc. in adjacent building
				Expelling plug				43	1.25			
24 ♦	1984 Weymouth (Dorset)	2 m to 3 m thick crust of sands and gravel over estuarial silty clays becoming firmer at greater depth	350 mm ϕ 15 m depth Some with enlarged base	Driving tube open ended	47.1 kJ	8.5	6.1	13	3.6			Top-driven
				Driving tube with shoe	47.1 kJ	8.5	8.3	13	4.4			
				Extracting tube		8.5	2.9	25	2.1			
				Enlarging base		25	2.2					
25 ♦	1984 Cambridge (Cambs.)	4.75 m to 6.75 m loose fill over gault clay becoming stiffer with depth	350 mm ϕ 10 m to 11 m depth with enlarged base	Driving tube	47.1 kJ	13	5.6	22	3.1	34	2.6	Top-driven, sensitive equipment in adjacent building
				Enlarging base		13	4.9	22	1.9	34	1.1	
				Extracting tube		13	4.6	22	2.5	34	1.6	
26 ♦	1984 London E14	Fill over Thames ballast	400 mm ϕ 5 m depth	Driving tube	47.1 kJ	5.5	10.7	12	5.9	21	3.4	Top-driven, close to main service pipes
				Extracting tube		5.5	3.2	12	2.8	21	2.0	
27 ♦	1984 Isleworth (Greater London)	Clayey fill/London clay	350 mm ϕ 10 m to 12 m depth Some with enlarged base	Driving tube	23.5 kJ	30	1.05	35	0.95	40	0.66	Top-driven, measured on suspended floor in a computer room
				Enlarging base		35	0.76					
				Extracting tube		30	0.55					

Table D.2 **Summary of historic case history data on vibration levels measured during driven cast-in-place piling (drop hammer)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s⁻¹	m	mm·s⁻¹	m	mm·s⁻¹	
28 ♦	1984 Portsmouth (Hants)	Dense fine sand	400 mm ϕ 4 m to 6.5 m depth	Driving tube open ended	47.1 kJ	50	1.2	63	0.72			Top-driven
				Driving tube with shoe		50	1.0	63	0.83			
				Extracting tube		50	0.37	63	0.31			
29	1984 London E1	Soft fill over dense Thames ballast below 4.5 m	400 mm ϕ 5.5 m to 6 m depth with enlarged base	Driving tube (fill)	N/R	10	2.2					Bottom-driven, measured at base of riverside wall
				Driving tube (ballast)		10	7.7					
				Expelling plug		10	3.6					
				Enlarging base		10	6.9					
30 ♦	1985 Enfield (Greater London)	Fill/dense gravel/ London clay below 5 m to 6 m	350 mm ϕ 9 m to 11.5 m depth Some with enlarged base	Driving tube (gravel)	47.1 kJ	9.2	37.9	18.5	17.3			Top-driven, measured on earth retaining embankment
				Driving tube (clay)		9.2	10.3	18.5	2.4			
				Enlarging base		19.5	1.8	29.7	1.1			
31 ♦	1985 Littlehampton (W. Sussex)	Fill/very soft silty clay/thin layer of gravel/weathered chalk below 8 m to 9 m	350 mm ϕ 10 m to 11 m depth with enlarged base	Driving tube	N/R	14	2.2	24	0.82	30	0.88	Bottom-driven
				Expelling plug		14	2.2	24	1.8	30	1.3	
				Enlarging base		14	2.3	24	0.88	30	1.0	
32 ♦	1985 Mitcham (Greater London)	Sub-surface crust of Hoggin/ London clay below 2 m to 3 m	350 mm ϕ 9 m to 12 m depth Some with enlarged base	Driving tube	47.1 kJ	28	3.2	34	2.8	42	1.7	Top-driven (listed building)
				Enlarging base		37	1.2					
				Extracting tube		28	1.7	34	1.5	42	0.84	

Table D.2 **Summary of historic case history data on vibration levels measured during driven cast-in-place piling (drop hammer)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
						m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
33 ♦	1985 Uxbridge (Greater London)	Fill (including pockets of gravel) London clay below 3 m	350 mm ϕ 5 m to 12.5 m depth Some with enlarged base	Driving tube	23.5 kJ to 35.3 kJ	10	4.2 (V)	14	2.2 (V)			Top-driven
				Driving tube after preboring		5.5	3.3	9	2.0	13	1.4	
				Enlarging base		5.5	2.8	9	3.5	13	2.8	
				Extracting tube		5.5	5.9	9	3.4	13	2.9	

Table D.3 **Summary of historic case history data on vibration levels measured during dynamic consolidation**

Ref. no.	Year and location	Soil conditions	Tamping weight	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			t			m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
34	1973 Corby (Northants.)		9	Pass 1	Up to 1.59 MJ	25	3.0*	225	0.16*			
				Pass 2	Up to 1.59 MJ	25	4.7*	120	0.33*			
35	1973 Belfast (Antrim)	Clay fill	10		1.47 MJ	8	42	26	3.6	44	1.75	Dropping onto virgin ground
					1.96 MJ	14	12	25	3.2	49	1.35	Dropping on to fill
					981 kJ	14	10	25	2.9	49	1.4	(Dropping on to fill)
36	1974 Teesside (Cleveland)	Hydraulic fill of clean sand with some pebbles	17	Pass 1	2.50 MJ	5	240	12	53	20	15.5	
				Pass 2	2.50 MJ	5	177	12	67	20	20.3	
37 ♦	1975 Canterbury (Kent)	Sand fill containing much fine silt	N/R		20 m drop	12	16.5	20	5.8	32	2.7	
					15 m drop	10	20.5	20	6	32	3.3	
					10 m drop	12	15.5	20	4.5	28	2.2	

Table D.3 **Summary of historic case history data on vibration levels measured during dynamic consolidation** *(continued)*

Ref. no.	Year and location	Soil conditions	Tamping weight	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			t			m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
38 ♦	1975 Glasgow Govan (Strathclyde)	Old docks backfilled with well-graded permeable granular fill	15	Pass 1	2.94 MJ	15	22	30	13.5	50	9	Comparison between various tamping weights and drop heights
				Post-treatment	2.94 MJ	15	30	30	12	50	8.3	
				Post-treatment	2.21 MJ	15	27	30	10	50	8.5	
				Post-treatment	1.47 MJ	15	27	30	10	50	6.5	
			15 (small base)	Post-treatment	2.94 MJ	15	35	30	12	50	8.0	
			2 (ball)	Post-treatment	392.4 kJ	15	9	30	2.5	50	2.0	
39	1975 Cwmbran (Gwent)	Loose fill in old clay quarry; depth 7 m to 20 m	N/R		20 m drop	27	5.8					
40	1976 Port Talbot (W. Glamorgan)	Slag fill	15		2.94 MJ	75	2.1	250	0.16			Measured at ground level
					2.94 MJ	75	7.2	250	1.4			Measured at top of 30 m high silo
41 ♦	1978 London SE16	Old docks backfilled with various materials including cohesive clay soils with substantial voidage; depth 9 m to 11 m	10	Pass 1	981 kJ	24	8.9	40	4.6	70	2.0	
					1.96 MJ	24	13.5	40	11.2	70	2.5	
	1979		10	Later pass	1.96 MJ	10	52.3	22	8.9	65	2.2	
			15	Later pass	2.94 MJ	16	15					
	1980		15	Pass 1	2.94 MJ	20	11.6	27	6.5	34	5.1	
	1981		15	Pass 1	3.24 MJ	150	1.6					
42 ♦	1979 Walsall (W. Midlands)		15	Pass 1	2.21 MJ	60	4.4					
					1.47 MJ	60	3.5					
					735.8 MJ	60	3.1					

Table D.3 **Summary of historic case history data on vibration levels measured during dynamic consolidation** *(continued)*

Ref. no.	Year and location	Soil conditions	Tamping weight	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			t			m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
43 ♦	1982 Southampton (Hants)	Old refuse tip; depth 3 m to 5 m	8	Pass 1	1.37 MJ	10	15.9	16	11.0	27	6.2	Measured on pipeline
				Pass 1	1.37 MJ	25	9.0	35	6.9	49	4.7	Measured on house
44	1983 Glasgow Finnieston (Strathclyde)	Shaley fill; depth 10.5 m	15	Pass 1	3.09 MJ	75	5.2	100	2.8			
45 ♦	1984 Kingswinford (W. Midlands)	Old sand quarry backfilled with mainly granular material including foundry sand	15		2.65 MJ	32.5	8.9					Tamping on very shallow fill
					2.65 MJ	19	8.5	36	6.3	50	3.3	Tamping on deeper fill
					2.65 MJ	150	0.89					
46 ♦	1984 Dudley (W. Midlands)	Old opencast mine, filled with colliery shale in cohesive matrix	8	Pass 1	1.26 MJ	70	4.6	85	3.2			Measured on 300-year-old building
				Pass 2	1.26 MJ	72.5	4.4	82.5	3.4			Measured on modern house
						65	3.7					
47 ♦	1984 Glasgow Kingston (Strathclyde)	Miscellaneous slightly cohesive fill; depth 6 m to 7 m	8	Pass 1	1.18 MJ	15	5.1	30	4.2	45	2.3	Deep cut-off trench between treatment area and monitoring position
				Pass 1	1.18 MJ	60	1.9	75	1.4	90	1.4	
	1985			Pass 1	1.18 MJ	15	12.7	30	5.4	70	3.0	Measured on metal rack 0.9 m above ground level
				Pass 1	1.18 MJ	15	24.3	30	9.7	70	5.5	Measured on metal rack 2.7 m above ground level

Table D.3 **Summary of historic case history data on vibration levels measured during dynamic consolidation** *(continued)*

Ref. no.	Year and location	Soil conditions	Tamping weight	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			t			m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
48 ♦	1985 Aberdeen (Grampian)	Demolition rubble, silty sands, peats, etc., overlying beach sand. Depth of fill up to 15 m	15	Pass 1	2.65 MJ	19	13.7	27	13.0	51	7.1	
				Pass 2	2.65 MJ	40	3.3					Very soft fill in this area
				Pass 2	2.65 MJ	55	6.1	70	5.1			
49 ♦	1985 Gravesend (Kent)	Old domestic fill including bottles overlying Thanet sands and chalk. Depth of fill 1.5 m to 6 m	8	Pass 1	1.26 MJ	50	2.8					
				Pass 2	1.26 MJ	50	2.6					
50 ♦	1985 Preston (Lancs)	Old brickworks clay pit backfilled with loose ash, bottles, etc. Depth of fill 1 m to 5.5 m	15	Pass 1	2.94 MJ	38	6.5					Fill very shallow
				Pass 2	1.47 MJ	38	8.1					
51 ♦	1985 Exeter (Devon)	Old quarry backfilled with rubble, clays and miscellaneous waste overlying hard shale. Depth of fill 4 m to 12 m	8	Pass 1	1.26 MJ	30	4.2					

Table D.4 **Summary of historic case history data on vibration levels measured during vibroflotation/vibroreplacement**

Ref. no.	Year and location	Soil conditions	Depth of treatment	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			m		kJ	m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
52	1973 Newport (Gwent)	Demolition rubble in old basements	N/R	N/R	3.0	3	7.9*	6	4.5*	12	2.7*	Vertical
						3	7.3*	6	6.3*	12	1.9*	Horizontal
53	1973 Manchester Central (Greater Manchester)	Unspecified fill	N/R	N/R	3.0	3.5	5.1*					Horizontal
54 ♦	1974 Worcester (Hereford and Worcester)	N/R	N/R	N/R	1.64	2.4	2.0					
55 ♦	1974 London E9	N/R	3	Airflush	3.0	6.5	12.7					Measured on ground surface
						13.0	10.5					Measured at mid height of 3 m high brick boundary wall
56 ♦	1974 Sandgate (Kent)	N/R	N/R	N/R	3.0	2	24.0	5	10.0	20	1.6	
57 ♦	1975 Hemel Hempstead (Herts)	Loose chalk fill	6	N/R	3.0	1	18.0	2	15.0	2.9	5.0	Vertical
						6.7	2.5	14.5	0.6			Vertical
58 ♦	1975 Oxford (Oxon)	Disused limestone quarry backfilled with rubble	3 to 4	N/R	3.0	12	2.6					
59	1975 Port Talbot (W. Glamorgan)	Soft alluvium with surface crust	9.2	Waterflush	3.0	8	3.2					Vertical
60	1976 Bradford (W. Yorks)	N/R	N/R	N/R	3.0	0.6	19	1.2	8			
61 ♦	1976 Sutton Coldfield (W. Midlands)	Backfilled sand quarry	3 to 4	Airflush	3.0	25	1.4					
62 ♦	1976 Oxford (Oxon)	As for no. 58	3 to 4	N/R	3.0	15	1.9	20	1.1			

Table D.4 **Summary of historic case history data on vibration levels measured during vibroflotation/vibroreplacement** *(continued)*

Ref. no.	Year and location	Soil conditions	Depth of treatment	Mode		Measured peak particle velocity (PPV) at various plan distances							Remarks
						Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			m			kJ	m	mm·s⁻¹	m	mm·s⁻¹	m	mm·s⁻¹	
63 ♦	1976 London SW11	Demolition rubble in old basements	2.5 to 4	N/R		3.0	4	10.1	6	6.7	10	2.1	
64	1976 Manchester Moston (Greater Manchester)	N/R	3	Airflush	P	3.0	14	2.1	29	0.36	60	0.21	Cut-off trench
65 ♦	1978 Doncaster (S. Yorks)	Wet crushed limestone fill surrounding ground granular with high water table	5	Waterflush		3.0	22	0.98	57	0.18			32 Hz
							22	0.45	57	0.13			21 Hz
66 ♦	1979 York (N. Yorks)	Ash and clinker fill overlying clay	3 to 3.5	Airflush	P	3.0	25	1.4					Some alleged architectural damage
					C	3.0	25	1.3					
67 ♦	1980 Nottingham (Notts)	Demolition rubble in basements	3	Airflush		3.0	4.5	16.7	12	8.1	22	2.6	Ground surface measurement
68 ♦	1980 Stanstead Abbots (Herts)	Fill over soft silty clay over ballast	2 to 4	Airflush		3.0	17	1.6					First floor timber beam
						3.0	17	0.82					Ground floor house wall
69	1980 Rochdale (Greater Manchester)	Mixed fill of clayey consistency	2 to 5	Airflush	P	3.0	2.5	17.8	4.5	5.8	6	5.7	Brief surge at end of penetration
					C	3.0	2	5.6	4.5	3.3			Shallow cut-off trench to protect service pipe

Table D.4 **Summary of historic case history data on vibration levels measured during vibroflotation/vibroreplacement** *(continued)*

Ref. no.	Year and location	Soil conditions	Depth of treatment	Mode		Measured peak particle velocity (PPV) at various plan distances							Remarks
						Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			m			kJ	m	$mm{\cdot}s^{-1}$	m	$mm{\cdot}s^{-1}$	m	$mm{\cdot}s^{-1}$	
70 ♦	1980 Datchet (Berks)	Silty sand fill over chalk or sand and gravel	1.5 to 3	Airflush	P	3.0	6	5.0	15	1.2			These holes partially prebored with 350 mm auger
					P	3.0	26	1.9	40	0.95			Measured at first floor level
					C	3.0	26	2.4					
					P	3.0	23	1.4	38	0.65			Measured at ground level
					C	3.0	23	1.7					No pre-boring of holes
71	1980 Belfast (Antrim)	Weak sandy clay	Up to 7	Airflush	P	3.0	5	2.9	8.3	1.9	8.3	1.5	
					C	3.0	3.5	5.0	5	2.4			
				Waterflush	P	3.0	3.8	1.4	6.6	0.78			
					C	3.0	3.8	1.1	6.6	0.81			
72	1981 Brigg (S. Humberside)	Fine silty sand	3	Waterflush	P	1.64	1.5	5.4	2.5	3.1	5	2.1	
					C	1.64	1.5	3.5	2.5	3.0	5	2.5	
73	1981 Huddersfield (W. Yorks)	Ash and brick rubble fill	3 to 3.5	Airflush	P	3.0	2.5	34.7	4.6	19.7	11.8	8.7	Ground surface measurements
					C	3.0	2.5	48.0	4.6	18.2	11.8	3.8	
					P	3.0	5.5	7.5	7.6	3.9			Measured on underground service pipe
					C	3.0	5.5	8.4	7.6	5.4			
74 ♦	1981 Cardiff (S. Glamorgan)	Backfilled railway cutting; slag fill	2 to 3	Airflush	P	3.0	6	3.5	20	0.57			
					C	3.0	6	3.3	20	0.78			
75	1982 Birmingham Hockley (W. Midlands)	Demolition rubble in collapsed basements	3	Airflush	P	3.0	5	2.6	8	1.6	11	1.1	Measured on old brick sewer
					C	3.0	5	3.5	8	1.8	11	0.98	
76 ♦	1983 Datchet (Berks)	Miscellaneous fill including dense fine sand and very loose sand	3	Airflush	P	3.0	8	4.9	12	3.8	20	1.3	Measurements on end terrace house with existing defects
					C	3.0	8	2.0	12	3.2	20	1.8	

Table D.4 **Summary of historic case history data on vibration levels measured during vibroflotation/vibroreplacement** *(continued)*

Ref. no.	Year and location	Soil conditions	Depth of treatment	Mode	Measured peak particle velocity (PPV) at various plan distances								Remarks
						Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			m			kJ	m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
77	1983 Rugeley (Staffs)	Demolition rubble fill to 3 m over sands and gravels	3	Airflush	P	3.0	6	16.1	10	8.6	22	2.0	Ground surface measurements
					C	3.0	6	8.6	10	5.8	22	1.9	
					P	3.0	4	35.2	7.5	4.5	16	1.4	Measured on top of retaining wall
					C	3.0	4	25.7	6.5	8.6	16	1.3	
78 ♦	1983 Tewkesbury (Glos)	Made ground including raised shingle	3	Airflush	P	3.0	6	12.5	15	2.9	27	0.87	
					C	3.0	6	9.1	15	3.1	27	0.87	
					P	3.0	3.5	22.3	10	15.5			Measurements on free-standing manhole surround
					C	3.0	3.5	25.7	10	11.6			
79 ♦	1983 Newcastle-upon-Tyne (Tyne and wear)	Ash and brick rubble fill	2.5 to 6	Airflush	P	3.0	5.5	2.5	7.5	2.0	15	1.5	Encountered buried obstruction
					P	3.0	11	2.6					
80	1983 Oxford (Oxon)	Miscellaneous fill over weak cohesive soil over gravel	2.2	Airflush	P	3.0	1.9	7.6	4	2.4	10.5	1.1	Cut-off trench
					C	3.0	1.9	6.9	4	2.3	10.5	0.55	
81	1983 London E1	Demolition rubble and other fill over gravel	1.5 to 2.5	Airflush	P	3.0	18	0.75	26	0.44	32	0.15	Sensitive industrial processes nearby
					C	3.0	18	0.76	26	0.62	32	0.15	
82	1984 London SW6	Brick rubble fill over clayey sand and sands and gravels	2.5 to 3	Airflush	P	3.0	3.5	12.6	5	10.7	18	1.6	Measured on service pipes
					C	3.0	3.5	16.5	5	10.3	18	1.7	
83 ♦	1984 Gravesend (Kent)	Ash, brick and demolition, rubble backfilled into old basements	2.5 to 3	Airflush	P	3.0	8	2.4	14	1.2			
					C	3.0	8	2.1	14	0.9			
84	1985 Dudley (W. Midlands)	Granular fill over clay over black coal shale	2.5 to 4	Airflush	P	3.0	3.5	7.4	6	5.4	15	1.4	Cut-off trench, measured on service pipe
					C	3.0	3.5	5.5	6	2.7			

Table D.4 **Summary of historic case history data on vibration levels measured during vibroflotation/vibroreplacement** *(continued)*

Ref. no.	Year and location	Soil conditions	Depth of treatment	Mode		Measured peak particle velocity (PPV) at various plan distances							Remarks
						Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
			m			kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
85 ♦	1985 Birmingham Bordesley (W. Midlands)	Miscellaneous fill over stiff clay	2 to 2.5	Airflush	P	3.0	3.5	7.7					Cut-off trench
					C	3.0	3.5	4.2					
86 ♦	1985 Hull (N. Humberside)	Miscellaneous fill over dense loamy sand	4	Airflush		3.0	12	8.1					
87 ♦	1985 Worcester (Hereford and Worcester)	Fill including sands, rubble and porcelain waste over dense gravel	3	Airflush	P	3.0	9	5.5	13	3.3	26	1.2	Cut-off trench

Table D.5 **Summary of historic case history data on vibration levels measured during the use of casing vibrators**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
88	1973 Isle of Grain (Kent)	Hydraulically placed sandfill over estuarial silts over ballast over London clay	815 mm ϕ 24.4 m depth permanent liner	Driving liner	4.35 to 6.3	1	10	2	3.2	3	0.8	25 Hz
				Driving liner	6.9 to 8.5	8	4.1	11	2.2	16	1.5	12 Hz to 15 Hz
89 ♦	1974 London W6	Fill over ballast over London clay	750 mm to 1 050 mm ϕ 2.5 m to 9 m depth	Driving casing	2.18 to 3.15	1.3	8.0	2	6.4	6.6	1.5	Vertical 25 Hz
				Extracting casing	2.18 to 3.15	2	5.0	6.6	3.2			Vertical 25 Hz Sensitive equipment in adjacent building
90 ♦	1976 London EC4	Fill over ballast over London clay	750 mm to 1 050 mm ϕ	Driving casing	2.18 to 3.15	3	5.8					25 Hz
91 ♦	1976 London E1	Fill over ballast over London clay	N/R	Driving casing	2.18 to 3.15	10	4	25	1.5			25 Hz

Table D.5 **Summary of historic case history data on vibration levels measured during the use of casing vibrators** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
92	1980 Newark-upon-Trent (Notts)	Alluvia/gravels/marl	750 mm ϕ 10 m depth	Driving casing	2.18 to 3.15	35	0.29	50	0.24	75	0.16	25 Hz
				Extracting casing	2.18 to 3.15	50	0.31	75	0.23			25 Hz Sensitive equipment in nearby building
93 ♦	1980 London E1	Fill/dry gravel/clay	900 mm ϕ 10 m depth	Extracting casing	4.35 to 6.3	40	1.3					17 Hz
94 ♦	1981 London SE1	Fill/gravels/clay	N/R	Driving casing	2.18 to 3.15	30	0.8					Vertical 25 Hz
95	1981 Reading (Berks)	Peat, silts and gravels/putty chalk with flints/firm chalk	600 mm to 1 050 mm ϕ 10 m to 15 m depth	Driving casing	2.18 to 3.15	8	4.6	16	1.1	24	0.24	25 Hz
				Extracting casing	2.18 to 3.15	4.5	5.8	10.5	0.7			25 Hz
96 ♦	1981 London EC3	Fill/dense ballast/clay	750 mm to 1 500 mm ϕ 9 m depth	Driving casing	2.18 to 3.15	30	0.88	73	0.19			25 Hz
				Extracting casing	2.18 to 3.15	25	1.5	65	0.11			25 Hz
97 ♦	1981 London SE1	Fill/ballast/clay	9 m depth	Extracting casing	2.18 to 3.15	25	1.5					25 Hz
98	1984 Barrow-in-Furness (Cumbria)	Hydraulically placed sand fill/boulder clay marl	1 350 mm ϕ 8 m depth concentric with	Driving outer casing	26.1	19	13.1					Warming up 10 Hz
			1 200 mm ϕ 17.5 m depth Permanent liner		15.35	19	9.2					17 Hz
99 ♦	1985 Hatfield (Herts)	Clay over gravels	90 mm ϕ 15 m depth anchor casing	Driving casing	1.25	11	0.8					Anchor casings driven at 30° to horizontal
				Extracting casing	1.25	8	1.3	11	0.8			

Table D.6 **Summary of historic case history data on vibration levels measured during rotary bored piling (including casing dollies)**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
100 ♦	1974 London W6	Fill/gravel/London clay	N/R	Driving casing		7	3.2					Horizontal
				With 3 t dolly		7	1.0					Vertical
101	1981 London EC3	Fill/dense ballast/ London clay	1 050 mm ϕ	Augering		20	0.05					Listed building nearby
				Auger hitting base of hole		20	0.23					
102	1982 Cheltenham (Glos.)	Fill/wet sand/lias clay	900 mm ϕ	Augering		9	0.2					Listed building adjacent to site
				Hammering casing with Kelly bar		9	0.8					
103	1983 Romford (Greater London)	Fill clay	350 mm ϕ 14.5 m depth	Augering		10	0.38	20	0.3	30	0.03	
				Dollying casing	11.8	10	1.1	20	0.55			2 t dolly
				Auger hitting base of hole		10	0.96					
				Spinning off		10	0.57	20	0.44			
104	1985 London W1	Fill/sand/clay	500 mm ϕ	Augering		10	0.4	15	0.1	26	0.02	
				Auger hitting base of hole		14	0.3	26	0.1			
				Mudding in		10	0.3	14	0.2			
				Spinning off		10	0.3					
				Dollying casing	11.8	10	1.0	14	0.8			2 t dolly
105	1985 St. Albans (Herts)	Sands and gravels over chalk	600 mm ϕ 12 m depth	Augering		3.5	0.23	8	0.04			
				Auger hitting base of hole		3.5	2.4	8	1.7			
				Spinning off		6	0.08	8	0.06			

Table D.6 **Summary of historic case history data on vibration levels measured during rotary bored piling (including casing dollies)** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
106	1985 Portland (Dorset)	6 m of soft ground over rock	600 mm ϕ 7 m depth	Augering		5	0.54					Sensitive equipment in adjacent building
				Surging casing		5	0.36					
				Twisting in casing		5	0.22					
				Spinning off		5	0.42					
				Boring with rock auger		5	0.43					
107	1985 Uxbridge (Greater London)	Fill including pockets of gravel over London clay	350 mm ϕ 7 m depth	Augering		5.5	0.13					Preboring for a driven pile

Table D.7 **Summary of historic case history data on vibration levels measured during tripod bored piling**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C1 ♦	1971 London WC2	Overburden over London clay	N/R	Driving casing	N/R	1	12.5					
C2 ♦	1971 London SW1	Sand and gravel over London clay	500 mm ϕ 17 m depth	N/R	N/R	11	2.6	42	0.31			
C3 ♦	Bury (Greater Manchester)	Sand and gravel/ soft silty clay/hard glacial till	300 mm ϕ	N/R	N/R	15	4.0					

Table D.8 **Summary of historic case history data on vibration levels measured during driven sheet steel piling**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C4 ♦	N/R Aldermaston (Berks)	3 m to 4 m sandy gravel over London clay	N/R	Air hammer driving sheets	15	12	0.05					Vertical
C5 ♦	N/R Bridlington (Humberside)	4 m to 5 m soft saturated sand over soft to firm clay	N/R	Air hammer driving sheets	6.4	6	1.1					225 blows per min
			N/R	Extracting sheets	7.6	6	0.44					150 blows per min
C6 ♦	N/R Canvey Island (Essex)	Clay/soft silty clay/ silty sand; high water table	Frodingham 3 N 8 m depth	Drop hammer driving sheets	4.5 t	35	3.0					Vertical
					Hammer drop N/R	35	0.5					Horizontal
C7 ♦	N/R Montrose (Tayside)	N/R	Larssen	Driving sheets	32 to 73	11.7	4					Vertical
C8 ♦	1971 London WC2	Overburden/ London clay	N/R	Diesel hammer driving sheets	N/R	1	20					
				Air hammer driving sheets	N/R	1	10					
C9 ♦	1974 Lancashire	Fill/firm to stiff boulder clay/sandy stony clay/firm boulder clay	N/R	Driving sheets		33	0.89*					Horizontal
C10	1978 Crail (Fife)	Clay/rock	N/R	Drop hammer driving sheets	39.2	15	0.79*					Vertical, pile in clay
						15	0.48					Vertical, pile on rock
C11 ♦	N/R Hull (Humberside)	Fill/6 m alluvium/ 4 m to 6 m peat, clay, sand and silt/1.3 m sand and gravel/5 m stiff clay/9 m dense sand/hard chalk	Larssen no. 6 34 m depth Penetration 1 m into chalk; 27 m in total	Diesel hammer driving sheets	71.6 to 143.2	30	1.1	130	0.1	250	0.025	Horizontal radial
						30	0.35	130	0.1	250	0.015	Horizontal
						30	0.6	130	0.1	250	0.025	Transverse vertical

Table D.8 **Summary of historic case history data on vibration levels measured during driven sheet steel piling** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C12 ♦	1978 Hazel Grove (Greater Manchester)	Stiff clay/dense sand including clay bands	Frodingham 2 N	Drop hammer driving sheets	19.9	11	16	26	12.5	54	2.6	
C13 ♦	1978 Oldham (Greater Manchester)	N/R	N/R	Diesel hammer driving sheets	N/R	60	2.5 +					Vertical
C14	N/R Cambridge (Cambs)	Loose to medium sands over clay	N/R	Driving sheets	N/R	2	10					Vertical
						2	2					Horizontal
C15 ♦	1979 Molesey (Surrey)	Gravel over London clay	N/R	Diesel hammer driving sheets	N/R	5	13.5					On bungalow
						5	40.4					On ground surface
C16	1979 Rochdale (Greater Manchester)	N/R	N/R	Driving sheets	N/R	6	1.9					
C17	N/R Cambridge (Cambs)	Fill/sand and gravel/gault clay	Frodingham 1 B 6 m depth	Drop hammer driving sheets	13.5	1	9.1*					
C18	1980 Newton Heath (Greater Manchester)	N/R	N/R	Driving sheets	N/R	300	0.015					Vertical
C19	1981 Denton (Greater Manchester)	Firm sandy glacial till	14 m depth	Diesel hammer driving sheets	N/R	0.9	15					Vertical

Table D.9 **Summary of historic case history data on vibration levels measured during driving of bearing piles**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C20	N/R Glasgow Cowcaddens (Strathclyde)	3 m fill, blaes, clay and boulders over 8 m soft to firm silty clay over sandstone	305 mm × 305 mm Steel H-pile	4 t drop hammer driving pile	N/R	13	0.19*					Vertical
C21	N/R Drax (N.Yorks)	Granular fill, lacustrine deposits, sand, sandstone	Precast concrete 400 mm × 400 mm	Diesel and drop hammers driving piles	24.5 to 88.2	3	13					Vertical
C22	N/R Kinneil (Central)	N/R	N/R	Driving pile	N/R	6	5.2 +					
C23	N/R Leeds (W. Yorks)	4 m fill/2 m alluvial granular soils/rock	Driven cast-in-place dimensions N/R	Driving pile	N/R	12	5.1	23	1.4			When driven 1.5 m
C24 ♦	N/R Middlesbrough (Cleveland)	22 m firm becoming stiff boulder clay over marl	Driven cast-in-place dimensions N/R	Driving pile	N/R	12	11.6	30	4.7	45	1.45	
C25	N/R Ravenscraig (Strathclyde)	N/R	305 mm × 305 m Steel H-pile	Diesel hammer driving pile	N/R	25	0.13 +					
C26	N/R Reading (Berks)	N/R	Driven cast-in-place dimensions N/R	Driving pile	N/R	60 90	0.07 0.12					Measured on fifth floor of office building
C27	1968 Wylfa (Gwynedd)	Rockfill and clay over mica schist	Steel H-pile	Diesel hammer driving pile	N/R	1	18					Vertical
C28	1969 Ince (Cheshire)	Alluvial peat and clay, boulder clay, sand, bunter sandstone	305 mm × 305 mm Steel H-pile	Diesel hammer driving pile	43.4	8	1.4					
C29 ♦	1972 Derby (Derbys)	N/R	400 mm to 450 mm ϕ Driven cast-in-place	Driving pile tube	N/R	15	2.2					
C30 ♦	1972/3 Bristol (Avon)	Fill and alluvium over keuper marl	Simulation test for driven shell piling	Dropping test weight on ground	58.8	25	0.7					Vertical on ground

Table D.9 **Summary of historic case history data on vibration levels measured during driving of bearing piles** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C31 ♦	1977 Southampton (Hants)	2 m to 3 m granular fill over bracklesham beds, very compact clayey fine sand	275 mm × 275 mm × 9 m depth pre-cast concrete piles	Drop hammer driving pile	N/R	25	2.45					Holes prebored to 3 m depth
C32 ♦	1977 Middlesbrough (Cleveland)	Made ground/9 m to 12 m firm to stiff laminated clay/4 m to 6 m glacial till/ hard keuper marl	480 mm ϕ Cast-in-place, piling length N/R	Drop hammer driving pile tube	294.2	27	7.4 +	55	3.3 +			Horizontal on ground
C33 ♦	1977/78 Kings Lynn (Norfolk)	10.4 m soft clayey silt and peat/5 m stiff kimmeridge clay/ hard laminated kimmeridge clay	406 mm ϕ Driven cased pile, depth N/R	Drop hammer driving pile	36.8	14	0.3					Vertical
C34	1978 South Shields (Tyne and Wear)	Loose to medium sand and silt/soft to firm laminated clay/stiff boulder clay/medium to dense sand and gravel over mudstone at 21 m to 25 m depth	305 mm × 305 mm Steel H-pile, depth N/R	Diesel hammer driving pile	36.3	1.1	9.5					
C35 ♦	1978/9 Hull (Humberside)	N/R	Raking precast concrete piles, dimensions N/R	Drop hammer driving pile	N/R	20	0.51					
C36 ♦	1979 London SE8	N/R	Driven shell piles, dimensions N/R	Drop hammer driving pile	N/R	16.5	2.1	33	1.95	46	0.9	
C37	1980 Caernarvon (Gwynedd)	Fill/gravels and clayey silts/hard glacial till	Driven cast-in-place, dimensions N/R	Driving pile tube	N/R	2.5	18.6	5 to 10	5.5			Distances N/R precisely
C38 ♦	1980 Haxby (N.Yorks)	1.9 m to 3.5 m Clayey sandy fill over soft to firm laminated clay	Driven cast-in-place, depth 4 m to 5.5 m, ϕ N/R	Driving pile tube	N/R	3.8	25.0	5.5	22.0			

Table D.9 **Summary of historic case history data on vibration levels measured during driving of bearing piles** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C39 ♦	1980 Leatherhead (Surrey)	N/R	Type and dimensions N/R	Driving pile	N/R	50	1.25					Measured on ground floor
						50	25					Measured in middle of 1st floor
C40 ♦	1980 Middlesbrough (Cleveland)	N/R	Driven cast-in-place, dimensions N/R	Driving pile tube	N/R	11	28.9	18	13.8	48	3.1	
C41	1981 Grangemouth (Central)	Soft alluvium	Driven shell piles, 450 mm × 36 m depth	Drop hammer driving pile	29.4	4.5	2.1	9.5	1.2			
C42 ♦	1981 London W6	4 m fill/2 m ballast/ London clay	Driven cast-in-place, dimensions N/R	Driving pile tube	N/R	12	6.7					
C43	1981 Winchester (Hants)	4 m to 5 m made ground/gravel/ chalk	Bottom driven cased pile 10.5 m depth	Driving pile	N/R	2 to 3	3 to 4					Occasional peaks up to 30 mm·s–1

Table D.10 **Summary of historic case history data on vibration levels measured during use of vibratory pile drivers**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C44 ♦	N/R Bridlington (Humberside)	4 m to 5 m soft saturated sand over soft to firm clay	Sheet steel piling, dimensions N/R	Driving or extracting	N/R	6	2.6	8	2.2			27.5 Hz
C45	N/R Glasgow Cowcaddens (Strathclyde)	3 m fill, blaes, clay and boulders over 8 m soft to firm silty clay over sandstone	450 mm ϕ casing, depth N/R	Driving casing	2.18 to 3.15	13	1.4*					25 Hz

Table D.10 **Summary of historic case history data on vibration levels measured during use of vibratory pile drivers** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
C46 ♦	N/R New Haw (Surrey)	1 m fill/8 m to 12 m dense fine and medium sand with silty clay lenses (Bagshot), Claygate beds, London clay	Casing dimensions N/R	Driving casing	N/R	7	44	10	23.5	17.5	18.5	25 Hz
				Extracting casing	N/R	7	53	15	27	25	2.9	25 Hz
C47	1968 Drax (N. Yorks)	N/R	N/R	Warming up to drive pile (Resonant pile driver)	N/R	2	10 to 15					70 Hz to 80 Hz
C48 ♦	1968 Hastings (E. Sussex)	4 m clay/8 m peat/ 2.5 m clay/1 m sandy silt with gravel/6 m stiff clay (Hastings beds)/ mudstone and siltstone	N/R	Resonant pile driver	N/R	6	2.5					70 Hz to 80 Hz
C49 ♦	1972 London EC4	Sand and gravel over London clay	N/R	Driving pile	2.18 to 3.15	10	0.55					25 Hz
C50 ♦	1975 Milngavie (Strathclyde)	N/R	Casings, dimensions N/R	Driving casing	N/R	5	2.5					27.5 Hz
				Extracting casing	N/R	5	2.0					
C51 ♦	1976 Glasgow (Strathclyde)	N/R	Sheet steel piling, dimensions N/R	Driving pile	N/R	10	11.0					25 Hz
C52	1979 Egham (Surrey)	N/R	Casings, dimensions N/R	Driving casing	N/R	1.6	18.9	3.2	16.3	4.8	11.2	25 Hz
C53 ♦	1979 Molesey (Surrey)	Gravel over London clay	Sheet steel piling, dimensions N/R	Driving sheets	2.18 to 3.15	5	4.3					25 Hz
C54 ♦	1980 London N1	Gravel over London clay	Casings	Driving casing	2.18 to 3.15	40	2.0					25 Hz
				Extracting casing		75	0.3					

Table D.10 **Summary of historic case history data on vibration levels measured during use of vibratory pile drivers** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
C55	1981 Rhondda Valley (Mid Glamorgan)	Glacial till/ gravelly sandy silt mixture with occasional cobbles	Sheet steel piling, Frodingham 3 N 12 m depth	Driving sheets	4.89	10	2.4	20	2.2	40	0.8	Vertical 26.6 Hz
C56 ♦	1979 Bromley (Greater London)	Gravel	Sheet steel piling	Driving sheets	N/R	3	42	9	3.8	25	0.95	Variable frequency up to 23.5 Hz

Table D.11 **Summary of miscellaneous historic case history data on vibration levels measured during piling and kindred operations**

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	mm·s^{-1}	m	mm·s^{-1}	m	mm·s^{-1}	
M1	c1970 London WC2	0.3 m fill/0.8 m clay and gravel/3.6 m dense sand and gravel/stiff London clay including clay stones	Impact bored (tripod) pile dimensions N/R	Driving casing	4.25	2.7	3.1*					Measured at footings adjacent to old listed timber framed building
				Boring gravel	4.25	2.7	1.0*	4.3	0.6			
M2	1971 Bristol (Avon)	Soft clays over sandstone/marl at 10 m to 11 m depth	Driven steel H-piles 305 mm × 305 mm × 12 m depth	Drop hammer driving piles	35.7	1.5	68.4*	3	50.2*	4.6	37.7*	4 t hammer 0.9 m drop, 3 t hammer 1.2 m drop, all ground surface measurements
					35.7	1.5	48.8*	3	39.4*	4.6	20.6*	
M3	1971 Stevenage (Herts)	Medium dense sands and gravels	Bottom driven cast-in-place piling	Drop hammer driving pile tube	127	3	116*	6.1	30.3*	9.1	25.1*	Ground surface measurements

Table D.11 **Summary of miscellaneous historic case history data on vibration levels measured during piling and kindred operations** *(continued)*

Ref. no.	Year and location	Soil conditions	Pile dimensions	Mode	Measured peak particle velocity (PPV) at various plan distances							Remarks
					Theoretical energy per blow	Plan distance	PPV	Plan distance	PPV	Plan distance	PPV	
					kJ	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	m	$mm \cdot s^{-1}$	
M4	1986 Reading (Berks)	5 m granular fill and medium dense sands and gravels over chalk	Open ended casing 610 mm O.D. 10 m depth	Hydraulic vibrator PTC 25H2 (27.5 Hz)	7.08 per cycle	8	5.8	11.5	3.8	16	2.9	On sewer 6.5 m below ground level
						8	7.2	11.5	5.6	16	3.0	Ground surface measurements
M5	1982 Edinburgh (Lothian)	Fill and clay over sands and gravels	Driven precast concrete piles 15 m to 21 m depth	Drop hammer driving piles	26.5 to 44.1	8	23.7	16	7.4	32	2.7	Ground surface measurements
M6	1982 Linlithgow (Lothian)	Softish ground unspecified	Driven precast concrete piles 12 m depth	Drop hammer driving piles	15.5 to 30.9	8	13.4	16	4.4	32	1.5	Ground surface measurements
M7	1982 Ulceby (Humberside)	1.5 m crushed and rolled limestone over cohesive soils over limestone or chalk	Driven precast concrete piles 18 m depth	Drop hammer driving piles	26.5 to 44.1	8	18.6	16	6.6	32	1.3	Ground surface measurements

Annex E (informative) Prediction of vibration levels

E.1 Prediction of vibration levels from construction activities

Hiller and Crabb [11] have derived empirical formulae relating resultant PPV with a number of other parameters for vibratory compaction, percussive and vibratory piling, dynamic compaction, the vibration of stone columns and tunnel boring operations (the latter also providing a groundborne noise predictor) from field measurements.

These predictions for a variety of scaling factors and parameter ranges are reproduced in Table E.1.

NOTE Tables E.1 and E.2 are reproduced with the permission of TRL Limited. Copyright Transport Research Laboratory 2000.

Use of these formulae enables a prediction to be made of resultant peak particle velocities (PPV) and, for some processes, can provide an indicator of the probability of these figures being exceeded.

Table E.1 **Empirical predictors for groundborne vibration arising from mechanized construction works**

Operation	Prediction question	Scaling factors (and probability of predicted value being exceeded)	Parameter range
Vibratory compaction (steady state)	$v_{res} = k_s\sqrt{n_d}\left[\frac{A}{x+L_d}\right]^{1.5}$	$k_s = 75$ (50%) $k_s = 143$ (33.3%) $k_s = 276$ (5%)	$1 \leqslant n_d \leqslant 2$ $0.4 \leqslant A \leqslant 1.72$ mm $2 \leqslant x \leqslant 110$ m
Vibratory compaction (start up and run down)	$v_{res} = k_t\sqrt{n_d}\left[\frac{A^{1.5}}{(x+L_d)^{1.3}}\right]$	$k_t = 65$ (50%) $k_t = 106$ (33.3%) $k_t = 177$ (5%)	$0.75 \leqslant L_d \leqslant 2.2$ m
Percussive piling	$v_{res} \leqslant k_p\left[\frac{\sqrt{W}}{r^{1.3}}\right]$	For piles at refusal: $k_p = 5$ For piles not at refusal: $1 \leqslant k_p \leqslant 3$, depending on soil type (Table E.2)	$1 \leqslant L \leqslant 27$ m $1 \leqslant x \leqslant 111$ m (where $r^2 = L^2 + x^2$) $1.5 \leqslant W \leqslant 85$ kJ
Vibratory piling	$v_{res} = \frac{k_v}{x^{\delta}}$	$k_v = 60$ (50%) $k_v = 126$ (33.3%) $k_v = 266$ (5%)	$1 \leqslant x \leqslant 100$ m $1.2 \leqslant W \leqslant 10.7$ kJ $\delta = 1.3$ (all operations) $\delta = 1.2$ (start up and run down) $\delta = 1.4$ (steady state operation)
Dynamic compaction	$v_{res} \leqslant 0.037\left[\frac{\sqrt{W_h}}{x}\right]^{1.7}$		$5 \leqslant x \leqslant 100$ m $1.0 \leqslant W_h \leqslant 12$ MJ
Vibrated stone columns	$v_{res} = \frac{k_c}{x^{1.4}}$	$k_c = 33$ (50%) $k_c = 44$ (33.3%) $k_c = 95$ (5%)	$8 \leqslant x \leqslant 100$ m
Tunnelling (groundborne vibration)	$v_{res} \leqslant \frac{180}{x^{1.3}}$		$10 \leqslant r \leqslant 100$ m
Tunnelling (groundborne noise)	$L_p = 127 - 54\log_{10} r$		$10 \leqslant r \leqslant 100$ m

A	maximum amplitude of drum vibration, in millimetres (mm)	v_{res}	resultant PPV, in millimetres per second (mm·s^{-1})
L	pile toe depth, in metres (m)	W	nominal hammer energy, in joules (J)
L_d	vibrating roller drum width, in metres (m)	W_c	energy per cycle, in kilojoules (kJ)
L_p	[A1) room sound pressure level, in decibels [dB(A)] (A1]	W_h	potential energy of a raised tamper, in joules (J)
n_d	number of vibrating drums	x	distance measured along the ground surface, in metres (m)
r	[A1) slope distance from the pile toe or tunnel crown, in metres (m) (A1]		

Table E.2 **Values of k_p for use in predictions of vibration from percussive piling**

Ground conditions	Value of k_p
All piles driven to refusal	5
Pile toe being driven through: Very stiff cohesive soils Dense granular soils Fill containing obstructions which are large relative to the pile cross-section	3
Pile toe not being driven through: Stiff cohesive soils Medium dense granular soils Compacted fill	1.5
Pile toe being driven through: Soft cohesive soils Loose granular soils Loose fill Organic soils	1

E.2 Prediction of vibration from blasting sites

For any particular site, a number of measurements of vibration at different distances from the blast can be used to produce a scaled distance graph. An example of such a graph is shown in Figure E.1. This plots the largest single component vibration against the distance *m* from the blast, divided by the square root of the maximum instantaneous charge. Vibration limits are commonly expressed as a statistical average to take account of the inherent variability of blasts. The scaled distance graph can be used as an indication of likely vibration magnitudes at various distances.

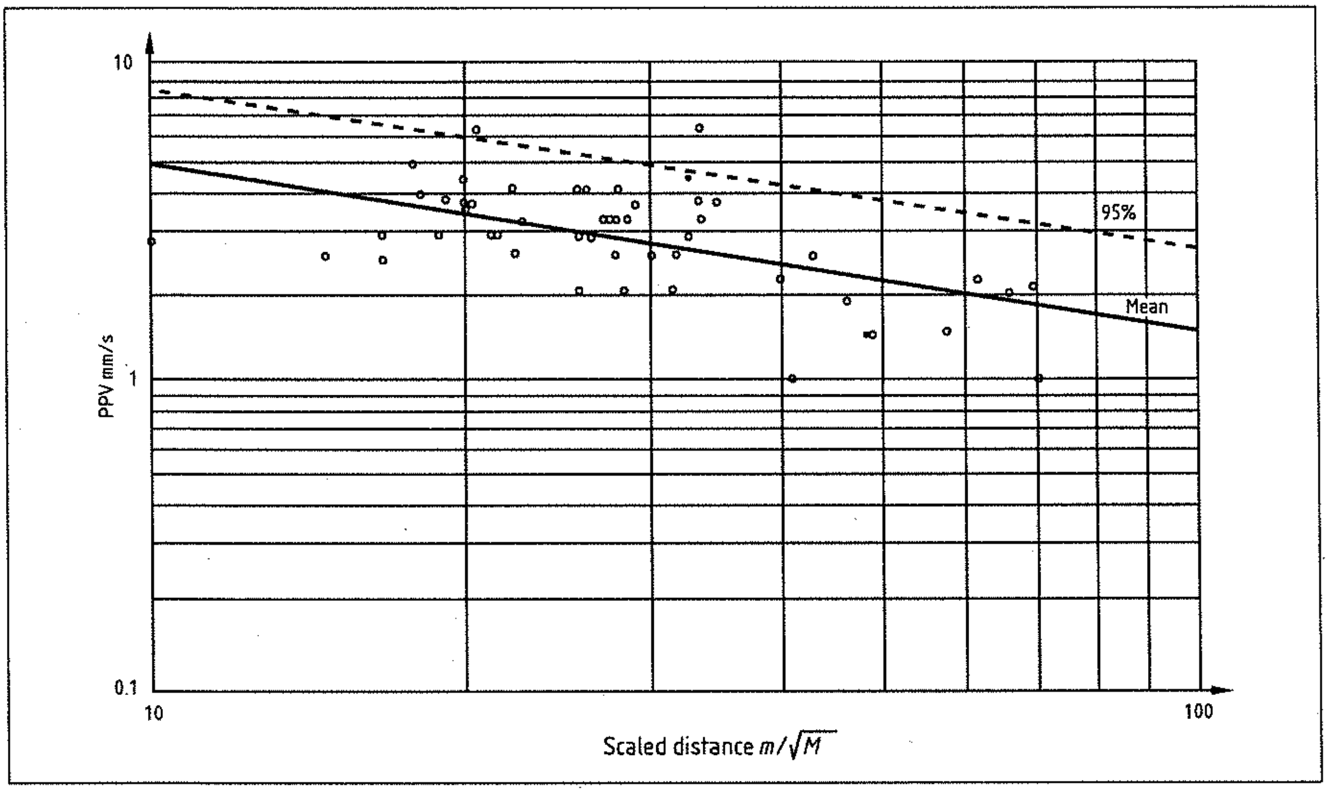
For the example shown in Figure E.1, in order to calculate *m* for 95% of blasts to be within 6 mm·s^{-1} for a maximum instantaneous charge *M* of 100 kg, carry out the following procedure:

a) from the Figure, read off the $\frac{m}{\sqrt{M}}$ value on the 95% line at 6 mm·s^{-1}. The answer = 20;

b) this means that $20 = \frac{\text{distance}}{\sqrt{100}}$;

c) therefore, distance = 200 m.

Figure E.1 **Scaled distance graph**



Annex F (informative) Description of vibration

NOTE F.1 to F.3 relate primarily, but not exclusively, to piling and kindred activities, and F.4 to F.6 relate primarily to surface mineral extraction

F.1 Types of vibration

Vibrations can be categorized in several ways as follows:

a) continuous vibrations in which the cyclic variation in amplitude is repeated many times;

b) transient vibrations in which the cyclic variation in amplitude reaches a peak and then decays away towards zero relatively quickly;

c) intermittent vibrations in which a sequence (sometimes regular, sometimes irregular) of transient vibrations occurs, but with sufficient intervals between successive events to permit the amplitude to diminish to an insignificant level in the interim periods.

Examples of these types of vibration within the piling field are:

1) continuous vibrations from a vibrating pile driver;

2) transient vibrations from an isolated hammer blow;

3) intermittent vibrations from a drop hammer pile driver.

NOTE Some air-operated hammers have sufficiently rapid striking rates to prevent the amplitude of vibration diminishing to an insignificant level between successive events (or impacts). In spite of the impulsive nature of the wave form the resulting vibrations can be described as continuous.

The response of soil and structures to continuous vibrations is to vibrate in sympathy with the vibrating source, i.e. at the same frequency or harmonics thereof. The resulting vibrations are, therefore, known as forced vibrations. Impulsive shocks giving rise to transient vibrations, on the other hand, excite the natural frequencies of the soil-structure combination and thus the resulting vibrations are known as free vibrations.

F.2 Characteristics of vibration

Vibrations are physically characterized as wave phenomena. They can be transmitted in one or more wave types, the most common of which are compression, shear and Rayleigh (or surface) waves. Each type of wave travels at a velocity which is characteristic of the material properties of the medium through which it is propagated. The wave velocity determines the time lag between the event at the source, e.g. the pile position and the remote receiving point. It does not, however, determine the severity of the vibration response at the remote receiving point, although the material properties of the transmitting medium play a significant role in this.

As the wave passes through the receiving point, the particles of matter undergo a vibratory or oscillatory motion. It is the intensity of these oscillatory particle motions which determine the vibration response at the receiving point.

The oscillatory motion can be characterized physically in terms of the following:

a) a displacement about the mean value *A*;

b) a particle velocity *v*;

c) an acceleration *a*;

d) frequency of the disturbance *f*.

In the case of sinusoidal wave propagation these parameters are simply related by the formulae:

$$v = 2\pi f A$$

A1 $a = 4\pi^2 f^2 A = 2\pi f v$ A1

where the symbols are each assigned their peak values.

It is not normally practicable to measure all four parameters simultaneously and indeed this is not generally necessary, since for the majority of frequencies of interest in piling operations the PPV is the best indicator of the vibratory response, especially when it is combined with the frequency content of the disturbance. Further guidance on human response to vibrations is given in BS 6472.

F.3 Vibrations associated with specific operations

F.3.1 Intermittent and transient vibrations

F.3.1.1 Single-acting pile hammers

Intermittent vibrations are obtained with most single-acting pile hammers. A variety of mechanisms can be used to raise the hammer after each blow, e.g. winch rope, diesel, hydraulic or compressed air.

Some diesel and air hammers are double acting and have considerably more rapid striking (or repetition) rates than conventional free fall hammers. This can result in vibrations being set up in certain circumstances (see Note to **F.1**).

F.3.1.2 Impact bored piling

Traditional impact bored piling gives rise to intermittent vibrations, both in the boring process when the boring tool is allowed to fall freely to form the borehole, and also when temporary casing is being driven or extracted.

F.3.1.3 Rotary bored piling

Although rotary bored piling tends to set up low level vibrations, transient vibrations can also occur when the auger strikes the base of the borehole. If it is necessary to insert an appreciable length of temporary casing to support the boring, a casing dolly can be used and, as with the impact bored piling method, this will give rise to intermittent vibrations. The use of special tools, such as chisels, will also result in intermittent vibrations.

F.3.1.4 Clamshell grabs

The construction of diaphragm walls and barrettes using clamshell grabs can give rise to transient or intermittent vibrations. The grabs can be operated either hydraulically, or by rope, but in each case they impact (with open jaws) on the soil in the trench. Since the excavation is filled with a bentonite suspension for temporary support there will be a modest buoyancy factor.

F.3.1.5 Free falling tamping weights

Ground treatment by dynamic compaction using large free falling tamping weights results in intermittent vibrations. The process is generally carried out on large sites to improve the density of relatively loose soils or fill materials. The major frequency content of the free vibrations tends to be very low.

F.3.1.6 Other operations causing intermittent vibrations

The formation of stone columns using plant designed for driven cast-in-place piling is another source of intermittent vibrations.

F.3.2 Continuous vibrations

F.3.2.1 General

NOTE See Table E.1 for variables that determine the intensity of vibration from sources of continuous vibrations.

Continuous vibrations differ from intermittent or transient vibrations in that the vibratory stimulus is maintained through a sequence of cycles. If the frequency of the vibrations coincides with a natural frequency of, for example, a structural element, then resonance can be induced. The resulting vibrations then exhibit substantially higher amplitudes than otherwise would be the case. This needs to be borne in mind if the criteria recommended in Annex B are used for the setting of acceptable limits for vibrations at the remote receiving point.

Continuous vibrations are associated primarily with vibratory pile drivers and vibratory compaction plant. Vibratory pile drivers are used for installing or extracting steel sheet and H-section piles and temporary or permanent casings for bored piles. Small vibrators are used for inserting reinforcement cages in continuous flight auger injected piles, and during the extraction of the driving tube following the concreting of a driven cast-in-place pile. The vibration in this latter case assists in compacting the concrete in the pile shaft, and the technique is employed as an alternative to hammering the tube during its extraction. Vibratory compaction plant is available in a wide range of sizes, for use in activities from reinstatement of excavated trenches to major earthworks construction.

F.3.2.2 Vibratory pile drivers

Vibratory pile drivers can be very effective in loose to medium, cohesionless or weakly cohesive soils. The continuous vibration of the pile member effectively fluidizes the immediately surrounding soil, removing contact friction during a fraction of each vibration cycle. The mechanism is thwarted in dense cohesionless soils and stiff cohesive soils, and a vibrator used at length under these circumstances merely succeeds in increasing the level of environmental vibrations at the expense of very slow penetration, especially with displacement piles.

Most vibratory pile drivers derive their cyclic axial motion from one or more pairs of horizontally opposed contra-rotating eccentric weights, which can be powered hydraulically or electrically. The design operating frequency of these vibrators is typically in the range 25 Hz to 30 Hz, which is rather higher than natural frequencies associated with loose or medium loose soil sites. This can lead to a high and possibly dangerous (although short-lived) response at the remote receiving station whenever the vibrator is switched on or off, as it accelerates or decelerates through the range either of site frequencies or of the natural frequencies of floor slabs, etc.

The introduction of variable moment resonance-free vibrators, as described in **8.5.3.10**, has enabled this unwanted effect to be minimized.

NOTE 1 As a guide, whole building response for buildings up to four storeys in height, as opposed to building element response, generally occurs at frequencies between 5 Hz and 15 Hz. Buildings element response, e.g. slabs, can occur at frequencies between 5 Hz and 40 Hz. For buildings more than four storeys in height, the whole building response frequency is likely to be less than 5 Hz to 12 Hz.

NOTE 2 Care is needed when using vibrators with frequencies less than 25 Hz.

F.3.2.3 Resonant pile drivers

A similar principle to that for vibratory pile drivers applies to very high frequency resonant pile drivers. In this case the vibrator is capable of oscillating at high frequencies (up to 135 Hz) and is designed to tune to one of the natural modes of vibration of the pile being driven, in order to obtain the benefits of pile resonance.

F.3.2.4 Continuous flight auger injected piling and pressed-in piling

The levels of vibration associated with continuous flight auger injected piling and pressed-in piling are minimal, as the processes do not involve rapid acceleration or deceleration of tools in contact with the ground but rely to a large extent on steady motions. Continuous vibrations at a low level could be expected from the prime movers.

F.3.2.5 Vibroflotation and vibroreplacement

In ground treatment processes by vibroflotation or vibroreplacement, a rotating eccentric weight in the nose of the machine sets up a mainly horizontal vibration pattern. This is basically a much enlarged version of the familiar vibrating poker used for compacting concrete. Pokers for vibroflotation are generally energized by electric or hydraulic motors and typically operate at frequencies between 30 Hz and 50 Hz.

F.3.2.6 Vibrating lances

Another ground treatment process is the installation of vertical band drains. This can be achieved by using a vibrating lance. The vibrator is similar in concept to, but somewhat smaller than, vibrators used for pile driving.

F.3.2.7 Other operations causing continuous vibrations

Continuous vibrations, albeit at low intensities, can be experienced from diesel engines, e.g. from impact bored piling winches mounted on skids, crawler mounted base machines, and attendant plant.

F.4 Ground vibration from surface mineral extraction

The primary cause of ground vibration on surface mineral extraction sites is blasting.

The level of vibration depends upon the distance from the blast, the maximum instantaneous charge weight of explosive, the delay sequencing and the geological nature and structure between the blast and receiver.

Other processes such as block making can give rise locally to ground vibration.

F.5 Criteria

[A1) BS ISO 4866:2010 (A1] gives information on the methodology for measurement, data analysis, reporting and building classification.

BS 7385-2 gives guidance on the assessment of the possibility of vibration-induced damage in buildings due to a variety of sources. This guidance indicates that the probability of damage tends towards zero at a component PPV of 12.5 $mm \cdot s^{-1}$.

BS 6472 provides guidance on human response to vibration. Guidance is given on the magnitudes of vibration at which adverse comment might begin to arise. Advice is given on vibration measurement, factors which influence human response and satisfactory vibration magnitudes.

[A1) Scottish Planning Advice Note PAN 50 [50] contains guidance on the control of vibration and air overpressure from blasting. (A1]

Further information is given in BRE Digest 403 [55].

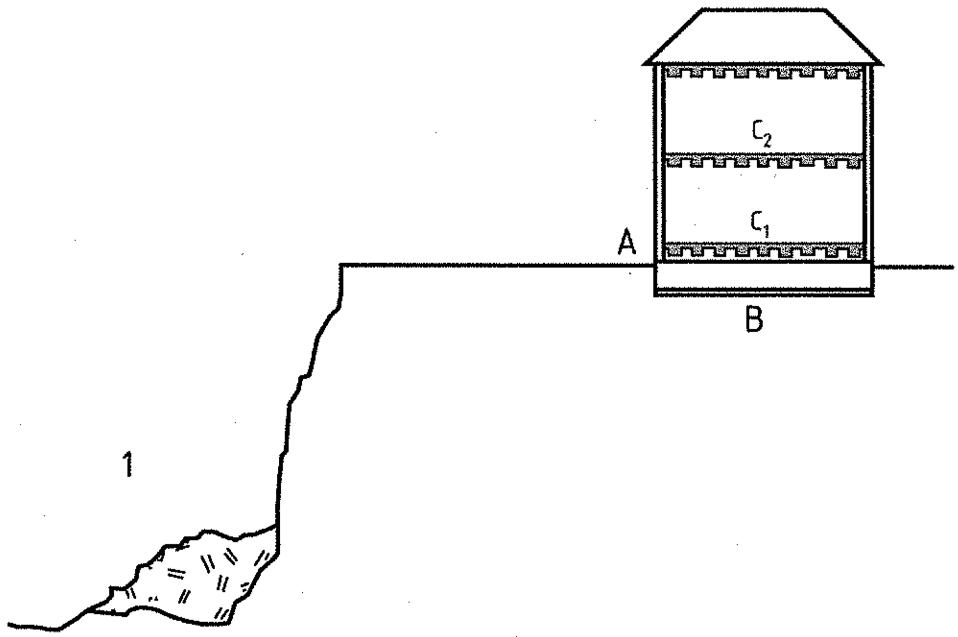
F.6 Measurement of vibration

Vibration from blasting can be measured with seismograph equipment, with geophones or with accelerometers.

The PPV in millimetres per second can be measured in three orthogonal axes at a point on the ground or inside a property. Figure F.1 shows a two-storey building neighbouring a quarry with possible measurement locations indicated. The difference between vibration levels on the ground and inside a property can be illustrated as follows.

A blast occurs and vibration travels through the ground. At point A it can be measured as a 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 C1, 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 C2, 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.

Figure F.1 **Sketch plan illustrating potential vibration measurement locations**



Key

1	Blasting face
A	Outside on ground
B	Inside on foundation
C_1	On timber joist or solid ground floor
C_2	On timber joist first floor

Annex G (informative) Air overpressure

G.1 Description

Whenever blasting is carried out, energy is transmitted from the blast site in the form of airborne pressure waves. These pressure waves comprise energy over a wide range of frequencies, some of which are higher than 20 Hz and therefore perceptible as sound, whereas the majority are below 20 Hz and hence inaudible, but can be sensed as concussion. It is the combination of the sound and concussion that is known as air overpressure.

The attenuation effects due to the topography, either natural or manufactured, between the blast and the receiver are much greater on the audible component of the pressure wave, whereas the effects are relatively slight on the lower frequency concussive component. The energy transmitted in the audible part of the pressure wave is much smaller than that in the concussive part and therefore baffle mounds or other acoustic screening techniques do not significantly reduce the overall air overpressure intensity.

Air overpressure can excite secondary vibrations at an audible frequency in buildings and it is usually this effect which has been found to give rise to comment from occupants. There is no known evidence of structural damage to structures from excessive air overpressure levels from quarry blasting.

Meteorological conditions, over which an operator has no control, such as temperature, cloud cover, humidity, wind speed, turbulence and direction, all affect the intensity of air overpressure at any location and cannot be reliably predicted. These conditions vary in time and position and therefore the reduction in air overpressure values as the distance from the blast increases might be greater in some directions than others.

G.2 Sources of blast-generated air overpressure

The use of detonating cord, inadequate or poor stemming and gas venting are major sources of air overpressure and can be controlled with good blast design. Sufficient stemming with appropriate material such as sized stone chippings is necessary. Gas venting can be minimized by good blast design, accurate drilling and careful placement of the correct amount of explosives. The other major sources of air overpressure from blasting are the reflection of stresses from a free face of an unbroken rock mass and also from the physical movement of a rock mass around the shot holes and at other free faces.

Detailed requirements for the use of explosives at quarries are contained in the Quarries (Explosives) Regulations 1988 [59] and the Quarries (Explosives) Regulations (Northern Ireland) 2006 [60].

G.3 Criteria

As the airborne pressure waves pass any single point the pressure of the air rises rapidly to a value above atmospheric pressure, falls to below atmospheric pressure, then returns to normal pressure after a series of oscillations. The maximum value above atmospheric pressure is known as peak air overpressure and is measured in pressure terms and generally expressed in linear decibels (dB lin) (see **G.4**).

Routine blasting can regularly generate air overpressure levels at adjacent premises of around 120 dB (lin). This level corresponds to an excess air pressure which is equivalent to that of a steady wind velocity of 5 $m \cdot s^{-1}$ (Beaufort force 3, gentle breeze) and is likely to be above the threshold of perception.

Windows are generally the weakest parts of a structure, and research by the United States Bureau of Mines [61] has shown that a poorly mounted window that is prestressed might crack at 150 dB (lin), with most windows cracking at around 170 dB (lin), whereas structural damage would not be expected at levels below 180 dB (lin).

G.4 Measurement

Measurement of air overpressure needs to be undertaken with microphones with an adequate low frequency response to fully capture the dominant low frequency component. A 2 Hz high pass system has been found to be satisfactory. Most of the equipment more commonly used for noise measurement is therefore not suitable for measuring overpressure. Although monitoring of air overpressure can be undertaken, due to the uncertainties with meteorological conditions, it is not possible to predict the location of the maximum air overpressure.

Additionally, pressure variations in the atmosphere due to windy conditions can mask the blast generated air overpressure levels. For these reasons it is not accepted practice to set specific limits for air overpressure. In order to control air overpressure the best practical approach is to take measures to minimize its generation at source.

Annex H (informative) Examples of record sheets

Investigators of piling vibrations might find the example pro forma record sheets in Figure H.1 and Figure H.2 helpful in formulating their own site record sheets. Figure H.1 and Figure H.2 are based on models extensively used by the University of Durham, whose permission to publish them in this annex is duly acknowledged.

Figure H.1 **Site measurements sheet**

Date	Time	Location	Disc	File
Ground conditions				
Ground surface		Subsurface		
Pile				
Type	Size			Length
Hammer				
Weight	Model			Energy
Geophones stand-off distances				
A	B	C	D	E
Additional observations				
File	Depth	Comments		
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

Figure H.2 **Vibration data summary sheet**

Disc no		Date				File name	
Pile							
Type		Sizes				Length	
Tubular steel		740 mm diameter and 7 mm thickness				20 m	
Hammer							
Frequency		Model				Energy	
27.5 Hz		Vibrodriver				10.7 kJ/cycle	
Peak particle velocity measurements mm·s^{-1}							
File no.	Depth (m)	Geophone-set Stand-off	A 2.8 m	B 4.0 m	C 8.0 m	D 10.0 m	E 15.0 m
H	7.0	Radial	14.6	6.3	0.73	3.5	1.4
O		Transverse	6.5	16.8	1.1	3.5	1.6
W		Vertical	12.2	13.1	2.1	3.6	1.5
8		Resultant	16.3	17.4	2.5	3.6	2.3
H	9.0	Radial	6.5	9.8	1.7	2.6	1.1
O		Transverse	6.4	14.0	1.3	3.0	2.0
W		Vertical	9.1	9.0	1.2	2.1	1.4
9		Resultant	11.3	17.4	2.1	3.6	2.3
H	11.0	Radial	14.3	9.8	4.0	4.1	0.9
O		Transverse	6.0	13.3	1.5	2.2	1.2
W		Vertical	10.2	10.9	4.9	5.0	1.9
10		Resultant	15.2	13.9	4.9	5.6	3.1
H	12.5	Radial	12.2	11.5	3.1	6.2	2.2
O		Transverse	13.8	18.7	2.6	5.1	1.6
W		Vertical	12.5	11.1	0.9	5.1	1.5
11		Resultant	18.6	21.9	3.2	7.1	2.5
H	13.0	Radial	15.3	11.5	4.5	6.0	1.7
O		Transverse	6.7	18.7	2.7	4.6	1.4
W		Vertical	15.5	13.2	5.2	3.3	1.6
12		Resultant	17.5	23.2	7.0	6.4	2.2

Bibliography

Standards publications

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 5228-1:2008, *Code of practice for noise and vibration control on construction and open sites – Part 1: Noise*

BS 5228-4:1992 (withdrawn), *Noise and vibration control on construction and open sites – Part 4: Code of practice for noise and vibration control applicable to piling operations*

BS 6187, *Code of practice for demolition*

BS 6472 (both parts), *Guide to evaluation of human exposure to vibration in buildings*

A1) *Text deleted* (A1

BS 7385-2, *Evaluation and measurement for vibration in buildings – Part 2: Guide to damage levels from groundborne vibration*

BS 6841, *Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*

A1) BS ISO 4866:2010, *Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and their effects on structures* (A1

ISO/FDIS 10137, *Bases for design of structures – Serviceability of buildings and walkways against vibrations*

ETS 300 019 (all parts), *Equipment engineering (EE) – Environmental conditions and environmental tests for telecommunications equipment*

Other publications

[1] GREAT BRITAIN DEPARTMENT OF THE ENVIRONMENT, TRANSPORT AND THE REGIONS. *The environmental effects of production blasting from surface mineral workings*. London: The Stationery Office, 1998.

[2] GREAT BRITAIN. Control of Vibration at Work Regulations 2005. London: The Stationery Office.

[3] HEALTH AND SAFETY EXECUTIVE. *Hand-arm vibration – The Control of Vibration at Work Regulations 2005 – Guidance on Regulations*. L140. Sudbury: HSE Books, 2005.

[4] HEALTH AND SAFETY EXECUTIVE. *Whole-body vibration – The Control of Vibration at Work Regulations 2005 – Guidance on Regulations*. L141. Sudbury: HSE Books, 2005.

[5] GREAT BRITAIN. Construction (Design and Management) Regulations 2007. London: The Stationery Office.

[6] GREAT BRITAIN. Construction (Design and Management) Regulations 1994. London: HMSO.

[7] GREAT BRITAIN. Construction (Health, Safety and Welfare) Regulations 1996. London: HMSO.

[8] HEALTH AND SAFETY EXECUTIVE. *Managing health and safety in construction – Construction (Design and Management) Regulations 2007 (CDM) – Approved Code of Practice*. L144. Sudbury: HSE Books, 2007.

[9] GREAT BRITAIN. Control of Pollution Act 1974. London: HMSO.

[10] GREAT BRITAIN. Environmental Protection Act 1990. London: HMSO.

[11] HILLER D. M. and CRABB G. I. *Groundborne vibration caused by mechanised construction works*. TRL Report 429. Wokingham: TRL, 2000.

[12] [A1) *Reference deleted* (A1]

[13] OFFICE OF THE DEPUTY PRIME MINISTER. [A1) *http://planningguidance.planningportal.gov.uk/blog/guidance/minerals/* (A1]

[14] HANSON, Carl E., TOWERS, David A. and MEISTER, Lance D. *Transit noise and vibration impact assessment*. FTA-VA-90-1003-06. Washington: US Department of Transportation, Federal Transit Administration, Office of Planning and Environment, 2006.

[15] GREAT BRITAIN. Pollution Control and Local Government (Northern Ireland) Order 1978. Belfast: HMSO.

[16] GREAT BRITAIN. Health and Safety at Work etc. Act 1974. London: HMSO

[17] GREAT BRITAIN. Health and Safety at Work (Northern Ireland) Order 1978. Belfast: HMSO.

[18] EUROPEAN COMMUNITIES. Directive 2002/44/EC of 6 July 2002 on the minimum health and safety requirements regarding the risks arising from physical agents (vibration). Luxembourg: Office for Official Publications of the European Communities, 2002.

[19] GREAT BRITAIN. Control of Noise (Appeals) Regulations 1975. London: HMSO.

[20] GREAT BRITAIN. Statutory Nuisance (Appeals) Regulations 1990. London: HMSO.

[21] GREAT BRITAIN. Control of Noise (Appeals) Regulations (Northern Ireland) 1978. Belfast: HMSO.

[22] GREAT BRITAIN. Control of Noise (Appeals) (Scotland) Regulations 1983. London: HMSO.

[23] GREAT BRITAIN. Building Regulations 2000 and subsequent amendments. London: The Stationery Office.

[24] GREAT BRITAIN. Building Standards (Scotland) Regulations 1990 and subsequent amendments. London: HMSO.

[25] GREAT BRITAIN. Building Regulations (Northern Ireland) 2000. London: The Stationery Office.

[26] GREAT BRITAIN. Building (Scotland) Act 2003. London: The Stationery Office.

[27] GREAT BRITAIN. Noise Insulation Regulations 1975. London: HMSO.

[28] GREAT BRITAIN. Noise Insulation (Scotland) Regulations 1975. London: HMSO.

[29] GREAT BRITAIN. Noise Insulation (Northern Ireland) Regulations 1995. Belfast: HMSO.

[30] GREAT BRITAIN. Land Compensation Act 1973. London: HMSO.

[31] GREAT BRITAIN. Land Compensation (Scotland) Act 1973. London: HMSO.

[32] GREAT BRITAIN. Land Acquisition and Compensation (Northern Ireland) Order 1973. Belfast: HMSO.

[33] GREAT BRITAIN. Highways Act 1980. London: HMSO.

[34] GREAT BRITAIN. Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1995. London: HMSO.

[35] [A1⟩ *Reference deleted* ⟨A1]

[36] [A1⟩ *Reference deleted* ⟨A1]

[37] GREAT BRITAIN. Coal Industry Act 1994. London: HMSO.

[38] GREAT BRITAIN. Coal Industry Nationalisation Act 1946. London: HMSO.

[39] GREAT BRITAIN. Opencast Coal Act 1958. London: HMSO.

[40] GREAT BRITAIN. Town and Country Planning Act 1990. London: HMSO.

[41] GREAT BRITAIN. Planning and Compulsory Purchase Act 2004. London: HMSO.

[42] GREAT BRITAIN. Town and Country Planning (General Development Procedure) Order 1995. London: HMSO.

[43] GREAT BRITAIN. Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations 1999. London: The Stationery Office.

[44] GREAT BRITAIN. Town and Country Planning (Scotland) Act 1972. London: HMSO.

[45] GREAT BRITAIN. Planning and Compensation Act 1991. London: HMSO.

[46] GREAT BRITAIN. Planning (Northern Ireland) Order 1991. London: HMSO.

[47] GREAT BRITAIN. Environment Act 1995. London: HMSO.

[48] [A1⟩ *Reference deleted* ⟨A1]

[49] SCOTTISH OFFICE DEVELOPMENT DEPARTMENT. *National Planning Policy Guideline 4 – Land for mineral working*. NPPG 4. Crown Copyright, 1994.

[50] SCOTTISH OFFICE DEVELOPMENT DEPARTMENT. *Planning Advice Note 50 – Controlling the environmental effects of surface mineral workings*. PAN 50. Crown Copyright, 1996.

[51] [A1⟩ *Reference deleted* ⟨A1]

[52] [A1⟩ *Reference deleted* ⟨A1]

[53] STEFFENS, R.J., *Structural vibration and damage*. BRE Report 69. Watford: BRE Press, 1974.

[54] HEAD, J.M. and JARDINE, F.M. *Ground-borne vibrations arising from piling*. CIRIA Technical Note 142. London: CIRIA, 1992.

[55] BUILDING RESEARCH ESTABLISHMENT. *Damage to structures from ground-borne vibration*. DG 403. Watford: BRE Press, 1995.

[56] UNGAR E.E., STURZ D.H. and AMICK C.H. Vibration control design of high technology facilities. *Sound and vibration*, July 1990.

[57] WHITE, D., FINLAY, T., BOLTON, M. and BEARSS, G. *Press-in piling: Ground vibration and noise during pile installation.* Proceeding of the International Deep Foundations Congress. Orlando, USA. ASCE Special Publication 116, PP 363–371. 2002.

[58] A1) *Reference deleted* (A1

[59] GREAT BRITAIN. Quarries (Explosives) Regulations 1988. London: HMSO.

[60] GREAT BRITAIN. Quarries (Explosives) Regulations (Northern Ireland) 2006. London: The Stationery Office.

[61] SISKIND, D.E., STACHURA, V.J., STAGG, M.S., and KOPP, J. W., *Structure response and damage produced by airblast from surface mining.* RI 8485. Washington D.C.: US Bureau of Mines Report of Investigations, 1980.

Further reading

NOTE These publications were listed in the previous edition of BS 5228. They are no longer specifically referred to in the standard but have been retained as they provide additional guidance.

CROCKETT, J.H.A. Piling vibrations and structural fatigue. *Proceedings of 1979 ICE Conference on recent developments in the design and construction of piles,* PP.305–320. London: Thomas Telford, 1980.

DOWDING, C.H. *Blast vibration monitoring and control.* Englewood Cliffs, New Jersey, USA: Prentice-Hall, Inc., 1985.

HEALTH AND SAFETY EXECUTIVE. *Control of Noise in Quarries.* HSG 109. Sudbury: HSE Books, 1993. ISBN 07176 0648 1.

INSTITUTION OF CIVIL ENGINEERS. *Specification for piling and embedded retaining walls.* Second edition. London: Thomas Telford Ltd, 2007. ISBN 9780727733580.

WALLER, R.A. (Roy Waller Associates). *Environmental effects of surface mineral workings.* Department of the Environment Research Report, London: The Stationery Office, 1994.

WISS, J.F. Vibrations during construction operations. *Proceedings of the American Society of Civil Engineers, Journal of the Construction Division.* 100 (CO3), September 1974, PP.239–246.

W.S.ATKINS ENGINEERING SERVICES (for The Department of the Environment). *The control of noise at surface mineral workings,* London, The Stationery Office, 1990. ISBN 0 11 752 338 0.

WYNNE, C.P. *A review of bearing pile types.* CIRIA Report PG. 1, January 1977: reprinted 1988. Available from CIRIA, Classic House, 174–180 Old Street, London, EC1V 9BP.

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