BS 6472-2:2008

BRITISH STANDARD

Guide to evaluation of human exposure to vibration in buildings

Part 2: Blast-induced vibration

ICS 13.160

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British Standards

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 17 and a back cover.

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Foreword

Publishing information

This part of BS 6472 was published by BSI and came into effect on 30 June 2008. It was prepared by Subcommittee GME/21/6, *Human exposure to mechanical vibration and shock*, under the authority of Technical Committee GME/21, *Mechanical vibration, shock and condition monitoring*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

Together with BS 6472-1:2008 this part of BS 6472 supersedes BS 6472:1992, which is withdrawn.

Information about this document

This part of BS 6472 contains guidance on the assessment of human response to vibration not available in ISO 2631-2.

BS 6472-1 and BS 6272-2 contain additional guidance and take account of recent developments in the subject. The layout of the standards differs substantially from previous editions. These present versions are intended to be more logical and accessible in their presentation of human perception to vibration.

BS 6472-2 deals with the particular problems associated with periodic blasting within range of occupied buildings: the guidance is a formalization of established, widely recognized techniques common in industry. BS 6472-1 offers guidance on how people inside buildings respond to building vibration other than from blasting.

A bibliography of appropriate supporting data published elsewhere is included.

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.

In particular, attention is drawn to the following statutory regulations and guidance notes.

Control of Pollution Act 1974 [1]

Town and Country Planning Act 1990 [2]

Environmental Protection Act 1990 [3]

Minerals Planning Guidance Note MPG9 [4]

Minerals Planning Guidance Note MPG14 [5]

Planning Advice Note PAN50, Annex D [6]

Minerals Technical Advice Note, MTAN (Wales) 1: Aggregates [7]

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1 Scope

This part of BS 6472 gives guidance on human exposure to blast-induced vibration in buildings. It is primarily applicable to blasting associated with mineral extraction. This part of BS 6472 might also be useful in assessing other forms of vibration that are caused by blasting, including when explosives are utilized in civil engineering works and in demolition activity. One-off explosive events such as bridge or building demolitions are outside the scope of this document.

This part of BS 6472 does not give guidance on the probability of equipment malfunction, building damage or injury to occupants in buildings subject to blast-induced vibration. Neither is guidance given on legal liability or vibration control and minimization. Advice on damage risk is given in BS 7385.

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.

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

BS EN ISO 8041, *Human response to vibration – Measuring instrumentation*

3 Terms and definitions

For the purposes of this British Standard, the following terms and definitions apply.

3.1 air overpressure
pressure wave in the atmosphere produced by a detonation of explosives

NOTE 1 Air overpressure consists of both audible (noise) and inaudible (concussion) energy.

NOTE 2 It is measured in pascals and usually reported in dB(lin).

3.2 data scatter
distribution of measured results

3.3 lapse rate
rate of fall of temperature with height

NOTE Lapse rate is measured in $°C \cdot km^{-1}$.

3.4 maximum instantaneous charge (MIC)
maximum amount (kg) of explosive detonated on any one delay interval

NOTE A typical blast consists of a number of boreholes. It is usually the case that each borehole is detonated individually by the use of detonators at specific delay intervals.

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3.5 scaled distance
slant distance between the blast and the receiver divided by the square root of the maximum instantaneous charge

NOTE Scaled distance is measured in $m \cdot kg^{-0.5}$.

3.6 slant distance
3-D vector distance between the blast location and measurement position obtained from coordinates in east-west, north-south and vertical directions

NOTE Slant distance is measured in metres (m).

4 Measurement and prediction of vibration

4.1 Characteristics of blast-induced vibration

Blast-induced vibration is impulsive in nature and a typical time history would be a rapid build-up to a peak followed by a decay which might or might not involve several cycles of vibration (depending on damping). In some cases, for example in some forms of underground mine blasting, there might be a number of such impulses in one blast vibration event.

The duration of an event at the point of measurement (typically one or two seconds) is dependent upon the magnitude of the blast, i.e. the number of delay intervals and explosive quantities, the method of detonation, separation distance and the intervening geology between the blast and the receiver.

A typical blast consists of a number of boreholes into which are placed the necessary explosive charges. It is usually the case that each borehole is detonated individually by the use of a series of detonators each with differing inherent millisecond delays.

Impulsive events, such as blast-induced vibration, are generally measured in terms of unfiltered time histories of three component particle velocities from which the peak values can be identified.

4.2 Measurement of vibration

For blasting, the current practice is to measure the peak particle velocity (ppv) using velocity transducers. Vibration measuring equipment or seismographs should be able typically to measure over the range 0.0001 $m \cdot s^{-1}$ (0.1 $mm \cdot s^{-1}$) to 0.1 $m \cdot s^{-1}$ (100 mm s^{-1}) over the frequency range 4.5 Hz to 250 Hz. Results obtained might differ slightly among sets of equipment.

Although velocity transducers are commonly used because they measure the desired parameters directly, other forms of instrumentation might be appropriate provided that the constant velocity characteristics can be derived.

The typical range of vibration frequency for blast-induced vibration is from 5 Hz to 40 Hz.

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Usually in the case of blast-induced vibration, measurements should be made outside the building on a well-founded hard surface as close to the building as possible. Alternatively transducers may be buried if no such surface is available. Guidance on appropriate methods of mounting transducers is available elsewhere [8].

NOTE There might be occasions when measuring inside a property is necessary, for example, for public relations purposes.

Since this British Standard is concerned with human response within buildings, the external levels are set so as to achieve satisfactory internal levels.

Calibration of equipment and traceability are important but outside the scope of this standard.

4.3 Prediction of vibration

In order to predict the likely vibration magnitude, a series of measurements at several locations should be taken from one or more trial blasts. The vibration measuring equipment should be located in an approximate straight line in the propagation direction of interest. Depending on the number of directions of interest, the local geology and the availability of equipment, several trial blasts might be needed. Scaled distance graphs can then be prepared for each direction of interest. The ppv in the three translational axes should be measured in $mm \cdot s^{-1}$ and the maximum component of the vibration identified for each measurement location.

The values should then be plotted against scaled distance on logarithmic scales where the scaled distance, s, is as follows:

$$s = d / \sqrt{C}$$

Where:

d is the slant distance from the blast in m;

C is the MIC in kilograms.

A graph similar to that shown in Figure 1 should result, specific to each site under consideration. The graph can then be used to indicate the likely vibration magnitudes at a given distance for a given MIC.

Differing geology and changes in blast design [9] result in data scatter and this should be taken into account in determining an adequate number of data points. Vibration limits should be expressed as a statistical average to take account of the data scatter.

The scaled distance approach can be a great help in designing blasts to achieve specific magnitudes of vibration at specific locations.

EXAMPLE

If the ppv limit is to be 6 $mm \cdot s^{-1}$ for 90% of the blasts and the MIC is 100 kg then from Figure 1 it can be seen that the scaled distance value on the 90% line at 6 $mm \cdot s^{-1}$ is 65 $m \cdot kg^{-0.5}$. This means that the slant distance d can be deduced from the following equation

$$s = d / \sqrt{C}$$

Where s is the scaled distance and C is the MIC.

Hence d is 650 m.

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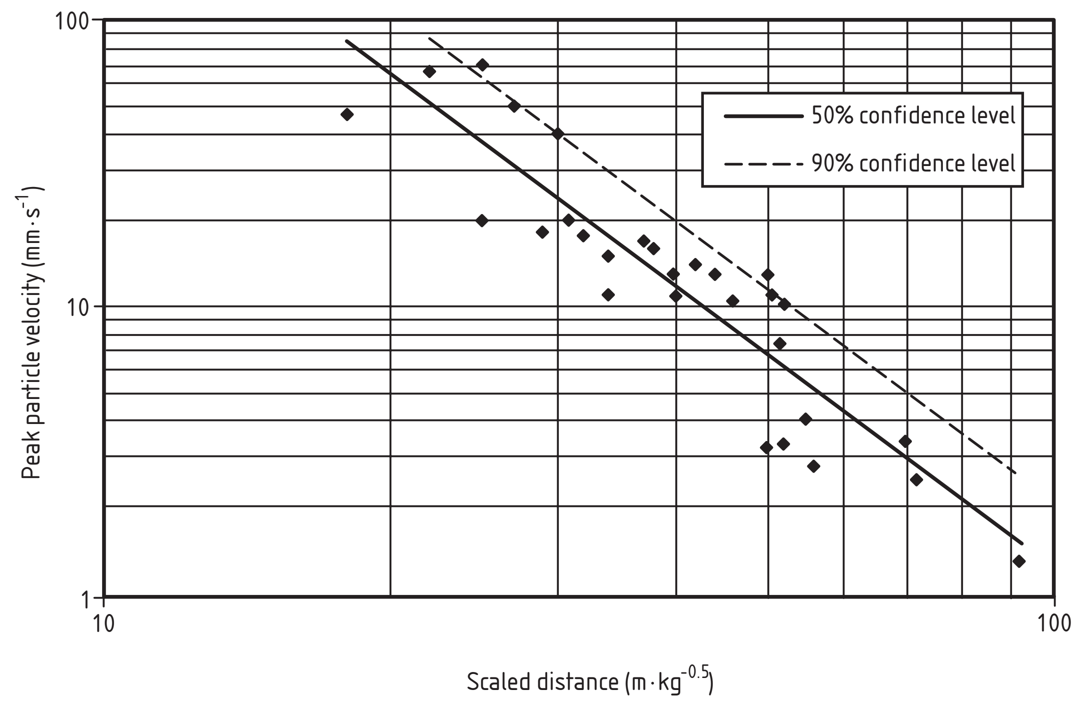
Similarly, if the vibration limit and slant distance are known then the MIC can be calculated.

The scaled distance data should be kept under regular review as blast monitoring continues through the operation of the site and the data set increases.

Figure 1 **Site-specific scaled distance graph**



5 Measurement and prediction of air overpressure

5.1 General

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 at frequencies higher than 20 Hz and are, therefore, perceived as sound. The majority of the airborne energy is carried at frequencies below 20 Hz and hence is inaudible to the human ear, but can be sensed as concussion or pressure. It is the combination of the sound and concussion that is known as air overpressure.

Any attenuation due to the topography, either natural or man-made, between the blast and the receiver is much greater for the audible higher frequency components of the pressure wave, with the lower frequency components being largely unaffected. The amount of energy transmitted in the audible part is relatively small compared with that transmitted in the inaudible part. Baffles, mounds and other acoustic screening techniques do not significantly reduce air overpressure levels.

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Air overpressure can excite secondary vibrations at audible frequencies in buildings and it is often this effect that gives rise to adverse comments from the occupiers. There is no known evidence of structural damage occurring in the United Kingdom as a result of air overpressure levels from blasting associated with mineral extraction. The highest levels normally measured in the United Kingdom are generally less than 1% of the levels known to cause structural damage [10].

The propagation velocity of air overpressure is at the speed of sound in air, i.e. about 340 $m \cdot s^{-1}$ and therefore it travels significantly slower than its associated ground-borne vibration.

This results in the air overpressure always arriving after the ground vibration onset and by several seconds if large distances are involved. Nevertheless, it is not readily possible for an observer to differentiate between these two sources and their respective effects and so any air overpressure significantly adds to the overall subjective blast experience.

5.2 Measurement of air overpressure

It is essential that the equipment used to measure air overpressure has an adequate low frequency response to capture fully the dominant low frequency component. It is for this reason that air overpressure magnitudes are measured using linear response, dB(lin), rather than with an A weighting, dB(A), as normally used in noise measurements. A 2 Hz high-pass system with an almost flat response down to 2 Hz should be used. If measurements include frequencies of less than 2 Hz they can be greatly distorted by even the slightest pressure changes, which can be caused by the gentlest of wind or people walking past the microphone.

5.3 Prediction of air overpressure

Accurate prediction of air overpressure is almost impossible due to the variable effects of the prevailing weather conditions and the large distances often involved.

Meteorological conditions, including air temperature, lapse rate, cloud cover, humidity, wind speed, direction and turbulence can all affect the magnitude of the air overpressure at any single location. Certain atmospheric conditions can produce a localized enhancement of the air overpressure in one direction. Data can be obtained from the nearest meteorological office, the lapse rate can be graphed and the risk of enhancement can be assessed. However, in practice these data are commonly obtained at some distance (often many kilometres) from the blast site and up to several hours before the detonation. Consequently the relevance of the data, and hence any prediction, could be doubtful for the location and time of blast, and the accuracy further reduced by the variability of the British weather [9]. Control of air overpressure should always be by its minimization at source through appropriate blast design.

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6 Satisfactory vibration magnitudes

6.1 General

Vibration associated with blasting has the potential to pose different problems from other sources of vibration, particularly since the vibration event is often accompanied by air overpressure. Many of the complaints about vibration from blasting might be due, either in part or entirely, to this air overpressure exciting the elements of the building, rather than groundborne vibration. Subjective separation of ground vibration and the effects of air overpressure is difficult.

NOTE Experience shows that the fear of property damage has a more significant effect on human response than the effect of the vibration on the person directly, although discussion of this matter is beyond the scope of this British Standard.

In residential situations comments about vibration are often made when the magnitudes are only slightly in excess of the perception levels. In the case of blasting, adverse comments might be made even below perception thresholds due to the influence of the air overpressure.

In the case of mineral extraction there might be some degree of acceptance through familiarity, particularly if the blasting occurs at the same time of day. There might be a trade-off between having several smaller blasts or one larger one, and generally speaking for a variety of reasons, including health and safety, operational constraints and environmental impact, the latter is the preferred option.

Satisfactory vibration levels for mines and quarries are usually set by the Mineral Planning Authority or Planning Authority as planning conditions.

Blast-induced vibration is highly variable, as illustrated in Figure 1. Satisfactory vibration magnitudes should not be exceeded by more than 10% of the blasts. No blast should give rise to vibration magnitudes that exceed the satisfactory level by more than 50%. Ideally the percentages should be calculated as a running average with as large a base of representative data as is reasonable, which would typically extend over a three month period.

Due to data scatter, working to a 90% confidence limit value means, in practice, that blasts need to be designed to ensure that the average level of vibration is approximately half of the specified limit. Since vibration levels at any specific location are related to a log-normal distribution the majority of vibration levels will be at or below this mean value. For example, if the satisfactory limit is required to be 6.0 $mm \cdot s^{-1}$ at 90% confidence then blasts will be designed to produce vibration levels of approximately 3.0 $mm \cdot s^{-1}$, and in practice most will be below this level of 3.0 $mm \cdot s^{-1}$.

Due consideration should be given to the time of the blasts, the period between the blasts and the number of blasts in a given time period. All of these could influence the perception of the satisfactory magnitude.

Column 3 of Table 1 details the maximum satisfactory magnitudes for vibration measured on a firm surface outside buildings with respect to human response. For blast vibration occurring up to three times per day the generally accepted maximum satisfactory magnitude for

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residential premises is a ppv of 6.0 mm·s^{-1}. However, when 6.0 mm·s^{-1} is considered to be too restrictive a value between 6.0 mm·s^{-1} and 10.0 mm·s^{-1} could be used. A transfer function of up to 1.3 has been found to be sufficient to determine likely indoor values. Hence the equivalent indoor satisfactory magnitude would be between 8.0 mm·s^{-1} and 13.0 mm·s^{-1}. However, amplification within a building is not always present, particularly if the location under consideration is a concrete floor at ground level.

The normal working hours for blasting for surface mineral extraction purposes can be regarded as 08h00 to 18h00 Monday to Friday, and 08h00 to 13h00 on a Saturday with no blasting on Sundays or Public Holidays. Blasting normally only takes place outside of these hours in the case of exceptional circumstances (for example, a safety emergency [4], [5], [6], [7]).

In general the human response recommendations given in this British Standard relate to long-term blasting operations such as from surface mineral extraction sites. For civil engineering projects, such as tunnels and foundation excavations, it should be recognized that the application of human response criteria, rather than conservative damage criteria, could significantly prolong project durations. In turn, this could lead to increased complaint levels, and could give rise to unreasonable cost implications. In these circumstances careful action by the operator, including negotiation, public relations and property surveys might result in agreed levels of vibration in excess of those recommended in this document.

In the case of projects where blasting has to take place outside the normal working hours given above, then the appropriate maximum satisfactory magnitude is 4.5 mm·s^{-1} except for the night-time period. During the night, from 23h00 to 07h00, a maximum vibration magnitude of 2.0 mm·s^{-1} is recommended, although ideally any vibration and air overpressure should be imperceptible at residential properties. These limits may be relaxed in special circumstances by prior negotiation with interested parties including the occupiers. It should be remembered that to ensure compliance with these maximum satisfactory magnitudes, blasts should be designed to produce levels of approximately half these values and, in practice, most blasts should be much less.

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Table 1 **Maximum satisfactory magnitudes of vibration with respect to human response for up to three blast vibration events per day**

Place	**Time**	**Satisfactory magnitude** [A] **ppv** mm·s^{-1}
Residential	Day [D]	6.0 to 10.0 [C]
	Night [D]	2.0
	Other times [D]	4.5
Offices [B]	Any time	14.0
Workshops [B]	Any time	14.0

NOTE 1 This table recommends magnitudes of vibration below which the probability of adverse comment is low (noise caused by any structural vibration is not considered).

NOTE 2 Doubling the suggested vibration magnitudes could result in adverse comment and this will increase significantly if the magnitudes are quadrupled.

*NOTE 3 For more than three occurrences of vibrations per day see the further multiplication factor in **5.2**.*

A) The satisfactory magnitudes are the same for the working day and the rest of the day unless stated otherwise.

B) Critical working areas where delicate tasks impose more stringent criteria than human comfort are outside the scope of this standard.

C) Within residential properties people exhibit a wide variation of tolerance to vibration. Specific values are dependent upon social and cultural factors, psychological attitudes and the expected degree of intrusion. In practice the lower satisfactory magnitude should be used with the higher magnitude being justified on a case-by-case basis.

D) For the purpose of blasting, daytime is considered to be 08h00 to 18h00 Monday to Friday and 08h00 to 13h00 Saturday. Routine blasting would not normally be considered on Sundays or Public Holidays. Other times cover the period outside of the working day but exclude night-time, which is defined as 23h00 to 07h00.

6.2 Greater than three blast vibration events per day

When more than three blast vibration events occur in a working day the following relationship should be used to apply an additional multiplying factor, F, to reduce the satisfactory magnitudes.

$$F = 1.7 N^{0.5} T^{-d}$$

Where:

N is the number of blast vibration events per day (and is greater than 3);

T is the blast vibration event duration typical for the site or sites;

d is zero where T is less than 1 s, 0.32 for wooden floors and 1.22 for concrete floors.

A blast vibration event is defined as a ppv exceeding 0.5 mm·s^{-1}, or background vibration, whichever is the greater. The duration is the length of time, in seconds, during which this level is exceeded.

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EXAMPLE 1

An open pit site requires blasting for overburden removal, with no more than three blasts per day being necessary. This site is adjacent to a residential area.

Table 1 details the relevant satisfactory magnitudes of vibration with respect to human response. In this case we are concerned with residential buildings during daytime and, therefore, ppv magnitudes from 6.0 $mm \cdot s^{-1}$ to 10.0 $mm \cdot s^{-1}$ are relevant. Normally 6.0 $mm \cdot s^{-1}$ would be used for the assessment of human response to blast-induced vibration.

Hence all blasts should be designed such that ppvs, as measured on a firm surface immediately outside of the most affected residential property, are less than 6.0 $mm \cdot s^{-1}$ for at least 90% of all blasts.

EXAMPLE 2

The same site as in example 1 now wishes to blast five times per day.

Since more than three events per day are envisaged the maximum satisfactory magnitude of 6.0 $mm \cdot s^{-1}$ is not now applicable. An F factor needs to be determined to further reduce the satisfactory magnitude.

In this case the number of events, N, is 5 and inspection of the vibration traces shows that typical vibration durations are 1.3 s. The relevant floor is concrete.

Thus:

$$F = 1.7 \times N^{-0.5} \times T^{-d}$$

$$= 0.55$$

Hence the maximum satisfactory magnitude of vibration is $6.0 \times 0.55 = 3.3$ $mm \cdot s^{-1}$ as measured on a firm surface outside the property.

7 Satisfactory air overpressure magnitudes

Windows are generally the weakest parts of a structure exposed to air overpressure. Research by the United States Bureau of Mines [8] has shown that a poorly mounted window that is pre-stressed can crack at around 150 dB(lin), with most windows cracking at around 170 dB(lin). Structural damage would not be expected at air overpressure levels below 180 dB(lin).

The air overpressure levels measured at properties near quarries in the United Kingdom are generally around 120 dB(lin), which is 30 dB(lin) below, or only 3% of, the limit for cracking pre-stressed poorly mounted windows.

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Due to the variable effects of the weather conditions at the time of any blast, the aim should always be to minimize air overpressure at the source by giving careful consideration to blast design and implementation. [4], [5], [6], [7], [9].

NOTE It is beyond the scope of this standard to describe in detail measures to reduce vibration and air overpressure. A range of practical advice is available that can be taken to reduce levels and their effects. Blasting techniques are continually changing and many of the changes will offer further opportunities to reduce vibration and air overpressure levels.

Specific advice can be found in the following documents:

Planning Advice Note 50 Annex D [6];

The Environmental Effects of Production Blasting from Surface Mineral Workings, DETR (Vibrock Limited), The Stationery Office 1998 [9].

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Annex A (informative) Suggested format and content of an assessment report

The assessment report needs to cite the person or body to whom it is addressed and refer to this British Standard.

In completing this report, it should be a conscious objective that sufficient information is provided to enable an experienced investigator to confirm the findings. The information to be reported needs to include some or all of the following, depending on the particular situation.

a) General information:
   - location(s);
   - dates and times;
   - person/people carrying out measurement(s) and assessment(s).

b) Information about the vibration under investigation:
   - frequency of occurrence;
   - receptor locations, building/floor/ground types, and vibration direction(s);

c) Instrumentation and analysis:
   - transducer(s) and calibrators: types and serial numbers, calibration history;
   - signal processing and recording equipment;
   - post-processing/analysis equipment, including details of software.

d) Measurement procedure:
   - locations of transducer(s);
   - method(s) of fixing transducer to measurement object or surface;
   - vibration parameters measured, number, times and duration of measurements;
   - calibration procedure(s);
   - background levels of vibration (in absence of source);
   - information about measurement surface, e.g. floor or ground, description of any preliminary tests carried.

e) Analysis procedure(s):
   - full explanation of how ppv is derived from measurement results;
   - information about any measured or estimated transfer functions used in the analysis (e.g. of seats, beds, or from external ground to floor of building).

f) Statement of results:
   - statement of measurement uncertainty and/or confidence limits of measured values.

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g) Results of predictions of levels of vibration:
   - results of any predictions, accompanied by details of the prediction method, of any assumptions or limitations involved, and of the input data.

h) Information about parallel effects:
   - all information about any parallel effects: structure-borne noise, airborne noise, induced rattling, visual effects, influence of a third party.

i) Assessment:
   - assessment method and results of the assessment(s), e.g. in terms of probability of adverse comment.

j) Subjective observations:
   - any other relevant observations not already included e.g. subjective impressions by the person carrying out the measurements, or anecdotal information conveyed to him or her by third parties.

Annex B (informative)

Derivation of the vibration prediction curve for a typical field site – An example

A series of blasts were monitored at a particular site where MICs (C) were 75 kg, 100 kg or 120 kg. For each vibration measurement location the slant distance (d) from the blast was determined and used, together with the associated MIC, to calculate the scaled distance (s) where:

$$s = d / \sqrt{C}$$

The maximum component of the vibration (peak particle velocity, ppv) recorded at each location is given in Table B.1 with the slant distances and MICs for each blast/measurement combination.

Regression analysis may be conducted as below to determine the equation of $\log_{10}$(ppv), y, as a function of $\log_{10}$(scaled distance), x (see Figure B.1). The data and values derived to conduct the statistical analysis are given in Tables B.1 and B.2. The analysis assumes that the distribution of y about the regression line is Gaussian. The linear regression line has the general equation:

$$y = mx + c$$

Where m is the gradient of the line and c the intercept and:

$$y = \log_{10}(\text{ppv}),\ x = \log_{10}(\text{scaled distance}).$$

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The upper 90% confidence level, y_{90}, is determined from the standard error of y on x; the equation of the 90% confidence boundary is given by:

$$y_{90} = mx + c + t_{90} \cdot se_{y.x}$$

where the standard error of y on x, $se_{y.x} = \sigma_y \sqrt{1 - r^2}$ and t_{90} is the critical value of t for the 90th percentile (one-tailed test).

The correlation coefficient $r = \dfrac{\sum (x - \overline{x})(y - \overline{y})}{N \sigma_x \sigma_y}$

where σ_x and σ_y are the standard deviations of x and y and N is the number of samples.

The gradient $m = \dfrac{\sum xy - N\overline{x} \cdot \overline{y}}{\sum x^2 - N\overline{x}^2}$

Therefore, m = (47.91 – (29 × 1.604 × 1.069))/(75.30–(29 × 1.604^2)) = –2.461 (from Tables B.1 and B.2).

The intercept $c = \overline{y} - m\overline{x}$. Therefore, the equation of the 50% confidence limit, as shown in Figure B.1, is:

$$y = -2.461x + (-2.461 \times [-1.604] + 1.069)$$

Or $y = -2.461x + 5.015$

The correlation coefficient $r = \dfrac{-1.814}{29 \times 0.1595 \times 0.4307} = -0.9110$ (satisfactorily high).

The standard error, $se_{y.x} = \sigma_y \sqrt{1 - r^2} = 0.4307\sqrt{1 - 0.9110^2} = 0.1777$; t_{90} is 1.282 for large values of N.

NOTE For N=20, t_{90} is reduced by 3%; for N=10, t_{90} is reduced by 8%.

Therefore, the equation of the 90% confidence upper boundary, as shown in Figure B.1, is:

$$y_{90} = -2.461x + 5.015 + (1.282 \times 0.1777) \text{ or}$$
$$y_{90} = -2.461x + 5.243$$

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Table B.1 **Data from measurements of blast vibrations**

Slant distance (d) m	**Maximum instantaneous charge (C)** kg	**Scaled distance (s)**	**Max ppv (mm·s^{-1})**	**log 10 (scaled distance) (*x*)**	**log 10 (ppv) (*y*)**
180	100	18	47	1.2553	1.6721
250	100	25	70	1.3979	1.8451
290	100	29	18.2	1.4624	1.2601
340	100	34	15	1.5315	1.1761
370	100	37	17	1.5682	1.2304
380	100	38	16	1.5798	1.2041
401	100	40.1	11	1.6031	1.0414
420	100	42	14	1.6232	1.1461
500	100	50	13	1.6990	1.1139
505	100	50.5	11	1.7033	1.0414
516	100	51.6	7.4	1.7126	0.8692
550	100	55	4.1	1.7404	0.6128
720	100	72	2.5	1.8573	0.3979
920	100	92	1.3	1.9638	0.1139
190.5	75	22	66	1.3424	1.8195
260	75	30.02	40	1.4774	1.6021
216.5	75	25	20	1.3979	1.3010
277	75	31.99	17.7	1.5049	1.2480
294.5	75	34.01	11	1.5316	1.0414
398	75	45.96	10.5	1.6624	1.0212
450	75	51.96	3.3	1.7157	0.5185
296	120	27.02	51	1.4317	1.7076
338	120	30.86	20	1.4893	1.3010
435	120	39.71	13	1.5989	1.1139
482	120	44	13	1.6435	1.1139
570	120	52.03	10.3	1.7163	1.0128
548	120	50.03	3.2	1.6992	0.5051
613	120	55.96	2.8	1.7479	0.4472
767	120	70.02	3.4	1.8452	0.5315

NOTE 1 The mean of log_{10}(scaled distance), $\bar{x}$, is 1.604.

NOTE 2 The mean of log_{10}(ppv), $\bar{y}$, is 1.069.

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Table B.2 **Example of data manipulation to derive regression line and confidence boundaries**

x·y	x^2	y^2	$(x-\bar{x})$	$(y-\bar{y})$	$(x-\bar{x})(y-\bar{y})$	$(x-\bar{x})^2$	$(y-\bar{y})^2$
2.0990	1.5758	2.7959	–0.3482	0.6028	–0.2099	0.1212	0.3634
2.5793	1.9541	3.4044	–0.2056	0.7758	–0.1595	0.0423	0.6019
1.8428	2.1386	1.5879	–0.1411	0.1908	–0.0269	0.0199	0.0364
1.8012	2.3455	1.3832	–0.0720	0.1068	–0.0077	0.0052	0.0114
1.9295	2.4593	1.5139	–0.0353	0.1611	–0.0057	0.0012	0.0260
1.9022	2.4958	1.4499	–0.0237	0.1348	–0.0032	0.0006	0.0182
1.6695	2.5699	1.0845	–0.0004	–0.0279	0.0000	0.0000	0.0008
1.8603	2.6348	1.3135	0.0197	0.0768	0.0015	0.0004	0.0059
1.8925	2.8866	1.2408	0.0955	0.0446	0.0043	0.0091	0.0020
1.7738	2.9012	1.0845	0.0998	–0.0279	–0.0028	0.0100	0.0008
1.4886	2.9330	0.7555	0.1091	–0.2001	–0.0218	0.0119	0.0400
1.0665	3.0290	0.3755	0.1369	–0.4565	–0.0625	0.0187	0.2084
0.7390	3.4496	0.1583	0.2538	–0.6714	–0.1704	0.0644	0.4508
0.2237	3.8565	0.0130	0.3603	–0.9554	–0.3442	0.1298	0.9128
2.4425	1.8020	3.3106	–0.2611	0.7502	–0.1959	0.0682	0.5628
2.3669	2.1827	2.5667	–0.1261	0.5328	–0.0672	0.0159	0.2839
1.8187	1.9541	1.6926	–0.2056	0.2317	–0.0476	0.0423	0.0537
1.8782	2.2650	1.5575	–0.0985	0.1787	–0.0176	0.0097	0.0319
1.5950	2.3458	1.0845	–0.0719	–0.0279	0.0020	0.0052	0.0008
1.6976	2.7636	1.0428	0.0589	–0.0481	–0.0028	0.0035	0.0023
0.8896	2.9436	0.2688	0.1122	–0.5508	–0.0618	0.0126	0.3034
2.4448	2.0498	2.9159	–0.1718	0.6383	–0.1097	0.0295	0.4074
1.9377	2.2183	1.6926	–0.1141	0.2317	–0.0264	0.0130	0.0537
1.7810	2.5565	1.2408	–0.0048	0.0446	–0.0002	0.0000	0.002
1.8307	2.7011	1.2408	0.0400	0.0446	0.0018	0.0016	0.002
1.7383	2.9457	1.0258	0.1128	–0.0565	–0.0064	0.0127	0.0032
0.8583	2.8873	0.2551	0.0957	–0.5642	–0.0540	0.0092	0.3183
0.7817	3.0552	0.2000	0.1444	–0.6221	–0.0898	0.0209	0.387
0.9807	3.4048	0.2825	0.2417	–0.5378	–0.1300	0.0584	0.2892

NOTE 1 $\Sigma x{\cdot}y = 47.91$.

NOTE 2 $\Sigma x^2 = 75.30$.

NOTE 3 $\Sigma y^2 = 38.54$.

NOTE 4 $\Sigma(x-\bar{x})(y-\bar{y}) = -1.814$. *The mean of* $(x-\bar{x})(y-\bar{y})$ *is* -0.06257.

NOTE 5 $\Sigma(x-\bar{x})^2 = 0.7374$. *The mean of* $(x-\bar{x})^2$ *is 0.02543. The square root of the mean (the standard deviation) is 0.1595.*

NOTE 6 $\Sigma(y-\bar{y})^2 = 5.380$. *The mean of* $(y-\bar{y})^2$ *is 0.1855. The square root of the mean (the standard deviation) is 0.4307.*

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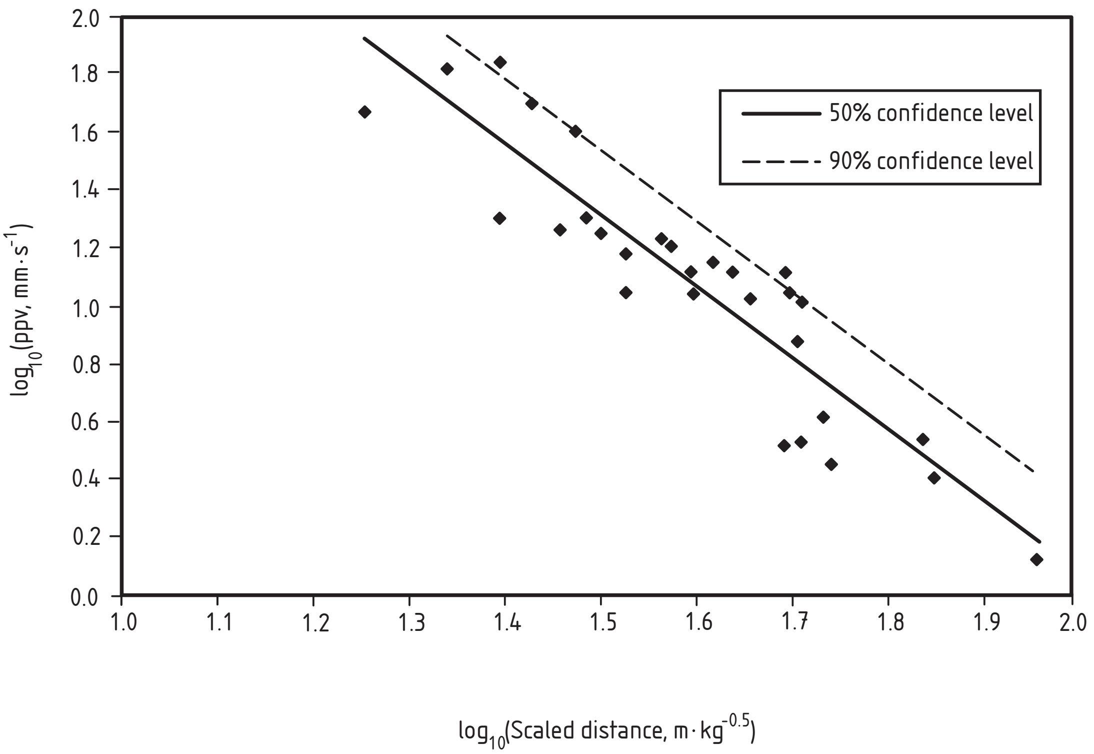
Figure B.1 **Logarithm of the peak particle velocity as a function of the logarithm of the scaled distance with 50% and 90% confidence levels**



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