Guidelines for Environmental Vibration Limits and Control

Third Edition

Department of Environment
Ministry of Environment and Water

GUIDELINES FOR ENVIRONMENTAL VIBRATION LIMITS AND CONTROL

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FOREWORD

Assalamualaikum Warahmatullahi Wabarakatuh & Salam Sejahtera

The *Guidelines for Environmental Vibration Limits and Control* hereby published by the Department of Environment is a new publication to supersede the previously published *Planning Guidelines for Environmental Vibration Limits and Control* (first edition 2004 and second edition 2007).

The preparation of this new Guideline was done as part of the updating of the Planning Guidelines for Environmental Noise and Vibration undertaken in the Ambient Noise Study Project by the Department of Environment (DOE) in 2017. This Guideline for vibration is an updated publication with revisions and updating of limits resulting from review and adoption of international standards. Additional guidance is provided in the revision that includes procedures and best practices in vibration measurements, predictions, assessment and mitigation. The publication of this Guideline is in line with the Department's responsibility for ensuring sustainable development in the course of national development while ensuring clean, healthy and safe environment in the country.

Consistent with DOE's role as a disseminator of information and promoter for continual appreciation of the natural environment in addition to its other roles, this Guidelines promotes self- regulation by the industries and other stakeholders in environmental noise & vibration management. The self-regulation and proactive measures in monitoring and mitigation of environmental noise & vibration are to support environmental, social and governance (ESG) initiatives required by parties responsible for the noise & vibration sources with impact to the environment and community.

I would like to acknowledge the expert contribution of the Institute of Noise & Vibration Universiti Teknologi Malaysia, in particular Professor Dr. Mohd Salman Leong, the relevant agencies and all other individuals in providing the input, comments and recommendations in the preparation and publication of this Guidelines.

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1.0 SCOPE

1.1 This document presents technical guidance and recommendations for

(a) specifying vibration limits in the environment, including buildings, to minimize disturbance from excessive vibrations.

(b) procedures on environmental vibration measurements and assessment.

1.2 For purpose of these guidelines, methodology and definitions used are consistent with those given in BS ISO 4866:2000 (or any subsequent revision). A glossary of definitions is included in this document.

1.3 These guidelines present vibration acceptance criteria and procedures for quantitative assessment of a vibration concern in the environment and buildings based on measured or calculated magnitudes.

2.0 PURPOSE

2.1 The purpose of these guidelines is:

(a) for planning, typically by project proponents, local authorities, government agencies, and consultants.

(b) for vibration impact assessments, pre- and post EIA compliance verification.

(c) for quantifying vibration disturbance on a quantitative basis; and

(d) for guidance in environmental vibration mitigation through planning and control.

3.0 LEGISLATIVE RELEVANCE

3.1 Approval of projects subjected to Environmental Impact Assessment (EIA) procedures and requirements usually stipulate requirements for vibration limits compliance at affected receptors during construction, and/or operation of the project.

3.2 The Department of Environment in these Guidelines present recommendations upon which acceptable vibration limits could be determined. In instances of projects or development, compliance to these limits may be made mandatory using legislative instruments available to the authorities (DOE, Local Authorities, City Halls, etc).

3.3 This Technical Guidelines supersede the DOE Planning Guidelines for Environmental Vibration Limits and Control, 2004.

4.0 TYPES OF VIBRATION

4.1 Vibration in the environment and in buildings can be caused by many different external sources. The vibration generated from these external sources propagate through the ground (commonly referred as groundborne vibration) and into buildings (referred as structure borne vibrations).

The vibrations may result in adverse human perception, discomfort or disturbance corresponding with human response to the vibration. The vibrations if sufficiently severe can result in cosmetic damage and even structural damage in buildings.

4.2 Vibration and its associated effects are usually classified as:

(a) Continuous vibration
(b) Impulsive vibration
(c) Intermittent vibration.

4.3 Continuous vibrations are vibrations that continuous uninterrupted for a defined time period, usually throughout the day and/or night. These are usually from machinery sources, steady state road traffic and continuous construction activities (such as tunnel boring in underground tunnels).

4.4 Impulsive vibration is a rapid motion build up to a peak followed by a damped decay that may or may not involve several cycles of vibration. Then duration of the vibration is short, typically less than 2 seconds. These are usually from blasting and activities such as dropping of heavy equipment, occasional loading and unloading.

4.5 Intermittent vibrations are interrupted periods of continuous vibrations, or repeated periods of impulsive vibration), or continuous vibration that varies significantly in magnitude.

It may originate from impulsive sources (e.g., impact pile driving, power presses) or repetitive sources (e.g., vibratory rollers compaction machines, jack hammers, hacking), and sources which would produce continuous vibration if operated continuously but are operated intermittently (e.g., intermittent construction activity, railways trains and heavy vehicles passing by).

5.0 VIBRATION LIMITS

5.1 Vibration in the environment are generated from physical sources or work process (vibration generation) that may be introduced to a location of concern that may or may not have other prevailing vibration sources and/or background activities.

This section of the Guidelines and Schedules presents recommended vibration limits that may be used to assess impact on receptors and building functionality. Vibration at the recommended levels while deemed acceptable may still be feelable to human perception.

5.2 The scope of vibrations considered in this Guideline is limited to vibrations propagation in the outdoor environment affecting receptors (human occupancy in buildings) and potential damage to the receptor's building.

5.3 Vibration limits may be set based on the following assessment considerations relating to:
(a) building damage.
(b) human comfort and annoyance.
(c) vibration sensitive equipment and processes.

5.4 The governing limits are dependent on the repetitive nature and duration of the vibration (continuous, intermittent, or single impulsive event), and sensitivity of receptors, buildings and equipment that are exposed to the vibrations.

Acceptable vibration levels are dependent on the type of receptors, type of building, functionality, and sensitivity at the location of concern which includes vibration sensitive equipment.

For human response and annoyance evaluation, different limits may be set for different period of the day and night.

5.5 It is often necessary to establish by measurements the existing ambient vibration in the absence of the external vibration source(s); and the contribution and severity of the vibration source(s) to be assessed against the existing ambient conditions.

5.6 Recommended generic vibration criteria for human occupancy and sensitivity of the receptors for a comprehensive range of buildings and equipment usage are given in First Schedule. The recommended limits and criterion ratings used are based on international best practices (ISO 2631, BS 6472, ASHRAE for different applications, space functionality and equipment sensitivity).

The vibration magnitudes are measured in velocity (RMS), and the recommended maximum velocity level stipulated in the Schedule. Corresponding vibration criterion limits for which vibration frequency spectral components (measured in octave band center frequencies) are also tabulated.

The range of vibration criterion rating curves are shown in Chart 1. These criterion curves are based on human response (BS 6472 and ISO 2631) where curve R=1 corresponding to 0.1 mm/s, measured in one-third octave bands in the frequency range 8 Hz to 100 Hz, is at the vibration human perception threshold. Other curves are based on multipliers (x2, x3, x4 etc.) of the human perception threshold (R-1, 0.1mm/s). Sub-integers (1/2, 1/4, 1/8, etc.) are designated as VC-A, VC-B, VC-C, etc.

The equivalent curves used in the American Society for Heating and Refrigeration Engineers (ASHRAE) Handbook are also stated in the Schedule.

Vibration sensitive equipment (typically used in laboratories, imaging system and micro-electronics) are governed by the functional requirements of the equipment related to detail size (vibration displacement). The recommended criterion curves for common generic equipment are given in the First Schedule.

The vibration shall be typically measured on the building floor slab or foundation; and in some instances, may also be measured on the equipment (at suitable mounting locations).

5.7 As an extension of the recommended limits for occupancy in buildings given in the First Schedule, recommended vibration limits for human response and annoyance from steady state continuous vibrations are given in the Second Schedule. These are deemed desirable limits consistent with different functions and type of receptors.

Recommended limits for human response and annoyance from intermittent vibrations (vibrations occurring intermittently over short durations) are given in the Third Schedule.

The limits are based on overall vibration velocity (ppv) measured in the vertical directions. The vibration criterion curves based on BS 6472 referenced to the threshold of human perception (Curve R=1, ppv=0.1mm/s vertical) are also stated.

5.8 Intermittent vibration can be assessed using the vibration dose value (VDV) that considers the amplitudes **and** duration of the vibration exposure. The VDV parameter is based on a weighted vibration acceleration level and considers the intermittent or varying nature of vibration. The vibration dose is fully described in BS 6472-1:2008 (and any revisions thereafter) which provides guidance for vibration assessment using the vibration dose value (**VDV**).

5.9 Vibration dose value (**VDV**) is derived in accordance with Equation 5-1 from the frequency weighted acceleration (in m/s^2) and total period of the day or night (in seconds) during which vibration occur. It is the fourth root of the integral with respect to the fourth power of the acceleration after it has been weighted for human response.

$$\mathrm{VDV}_{b/d,day/night} = \left(\int_0^T a^4(t)dt \right)^{0.25} \quad (5\text{-}1)$$

Where:

$\mathrm{VDV}_{b/d,day/night}$ 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 s) during which vibration can occur.

As a screening method for intermittent vibration, the vibration dose can be estimated (eVDV) as follows:

$$\mathrm{eVDV} = k \times a_{rms} \times t^{0.25} \quad (5\text{-}2)$$

where k = 1.4 (nominal value for crest factors below 6).
a_{rms} = weighted rms acceleration (m/s^2)
t = total cumulative time (secs) of vibration events or duration.

For crest factors above 6m the eVDV equation may no longer be accurately represented and the VDV in equation 5-1 should be used.

Vibration velocity can also be used to broadly estimate VDV. The vibration dose based on velocity (v_{rms} mm/s) can be estimated as follows:

$$\mathrm{eVDV} = 1.4 \times (2\pi f/1000)\, v_{rms} \times t^{0.25} \quad (5\text{-}3)$$

where f is the dominant vibration response frequency.

If f is not known, assume f = 8 Hz (for vibration in buildings), the approximation is

$$\mathrm{eVDV} = 0.07\, v_{rms} \times t^{0.25} \quad (5\text{-}4)$$

For vertical vibration, the weighting is based on curve W_b and the VDV determined according to this weighting is termed VDV_b.

The vibration dose value ranges for which might result in various probabilities of adverse comment within buildings as reproduced from BS 6472-1: 2008 are given in the Fourth Schedule. The corresponding anticipated environmental impact is stated for the different VDV values.

5.10 For the purpose of assessment for concern of damage in building, assessment against potential damage limits may be carried out.

Damage in buildings from vibration is related and inter-dependent on numerous factors. These include, but are not limited to, structural design and integrity of the building, materials, quality of construction and workmanship, age of building, characteristics of the vibration generated defined by its excitation forcing frequencies (rate of forcing), amplitude, and duration of vibration. There is a statistical probability whether potential structural damage may or may not occur.

The recommended limits do not guarantee absence of damage but reduce its probability of occurrence. The vibration limits as prescribed in these Guidelines are offered as guidance only, and in critical cases shall require a more detailed engineering assessment (based on vibration and/or dynamic strain and fatigue evaluation).

5.11 Guidance values for continuous vibrations relating to cosmetic damage as recommended in BS-7353-2: 1993 and are given in the Fifth Schedule.

Guide values for intermittent vibrations relating to cosmetic damage based on recommendations of BS-7353-2: 1993 and are given in the Sixth Schedule.

The corresponding limits plotted in a chart from frequency range 4 Hz to 160 Hz are given in Figure 2 and Figure 3 respectively.

5.12 Recommended vibration limiting values for cosmetic damage based on recommendations of DIN 4150-2 using the vectoral sum of vibration levels in three orthogonal axes (peak particle velocity tri-axial measurements in x, y and z directions) measured on building foundations are given in Figure 4.

5.13 Recommended vibration limits with respect to human response for single event impulsive excitation (up to three impulsive events, typically blast vibration events) are given in the Seventh Schedule based on recommendations of BS 6472-2:2008.

5.14 Recommended vibration limits assessed against potential cosmetic damage for single event impulsive excitation (up to three impulsive events, typically blast vibration events) are given in the Eighth Schedule based on recommendations of BS 6472-2:2008.

5.15 Vibration measured inside buildings may be amplified by building resonance and flexibility of the building elements for which adjustment to the limits (lower limits than values as tabulated) in Schedule may be applied.

5.16 When short term works such as piling, demolition and construction give rise to intermittent and/or impulsive vibrations, undue restrictions on vibration values to comply with the recommended limits may significantly prolong these operations and result in greater annoyance.

Short term works are works that occur for a duration of approximately one to two weeks. Under such circumstances it is allowable that higher vibration values (that are occasionally above recommended limits) when feasible and reasonable mitigation measures have been applied, and the project has broad community benefits, subject to review by the Authorities (Department of Environment, Majlis Perbandaran).

5.17 A tabulation summarizing vibration types and the appropriate assessment tables to be used is given in Table 5-1.

Table 5-1: Vibration Types and Applicable Assessment Schedules

Type	Continuous Vibration	Intermittent Vibration	Impulsive Vibration
Description	Vibrations that are continuous, uninterrupted for a definite time period	Vibrations from interrupted periods of continuous vibrations, or continuous vibrations with varying magnitudes, or repeated periods of impulsive vibrations	Vibrations that are transient with instantaneous rapid build up to a peak followed by a decay. Vibration is short (typically less than few seconds)
Typical Sources	Machinery operations, continuous construction activities (e.g., tunnel boring, slurry treatment plant), steady state road traffic	Impact pile driving, intermittent construction activities (e.g., hacking, jack hammers, mechanized rock breaking, demolition), power press, railway trains, heavy vehicles passing by	Blasting using explosives or similar methods, dropping of heavy loads
Assessment*			
Human comfort	Second Schedule	Third Schedule, Fourth Schedule	Seventh Schedule
Cosmetic damage	Fifth Schedule	Sixth Schedule	Eighth Schedule
Generic	First Schedule, Ninth Schedule	First Schedule, Ninth Schedule	First Schedule, Ninth Schedule

**Refer to Schedules of Recommended Vibration Levels*

6.0 VIBRATION MEASUREMENTS

6.1 Measurements of vibration are often necessary for one or combination of the following purpose:

(a) assessing vibration prevailing in the environment.
(b) assessing compliance to vibration limits for vibration sources and/or project development; or
(c) assessing environmental impact and potential receptors' response.

6.2 Vibration measurements shall usually include the following:

(a) prevailing vibration at a receptor location(s) and/or at the real property boundary of a source(s). These may be undertaken at locations prior to a project development. It could also be undertaken in the absence of the source(s) operating (for example with a plant not operating, or without construction activities).
(b) vibration levels at a receptor location(s) and/or at the real property boundary of a source with the plant operating, construction in progress, and/or completion and operation of a project (transit trains, industrial plant, etc.).
(c) vibration characteristics of each source as may be required to evaluate the contribution of each source.

6.3 Vibration measured indoors may be undertaken outdoors in the open environment on the ground (groundborne vibration) or at the building structure (building vibration) on building floor slabs or foundation as appropriate.

6.4 Descriptors and units of measurements for vibration are given in Annex A. Examples of basic vibration calculations (conversion of measurement measurements, calculation of vibration dose value VDV) are also given.

6.5 Procedures for vibration measurements for environmental impact assessment are given in Annex B. Measurement instrumentation and techniques for environmental vibration measurements are also described.

6.6 Examples of good and bad practices in vibration measurements in addition to issues relating to locations and sensors installations are given in Annex B. Errors and bad practices in the measurements shall result in inaccurate and/or unacceptable results.

7.0 MONITORING LOCATIONS

7.1 Vibration measurement and assessment shall be undertaken at locations where the vibration affects receptors (people or facilities) or nearest possible location to the receptors (for example at the perimeter boundary).

7.2 Vibration monitoring in general shall be undertaken at similar sensitive receptors (typically residential, schools, institutional, commercial, etc.) or critical receptors (vibration sensitive facilities or utilities, etc.) where vibration is of concern or where an impact assessment is required.

7.3 Measurement locations shall be at the real property boundary of the receptors of concern, or where feasible at the receptors' buildings.

7.4 The vibration assessment should normally be at the nearest building and/or locations of the vibration sensitive receptors. The best position for the monitoring point(s) are often on the floor slab on grade and/or foundation. Monitoring points shall in principle could be accessible to all parties concerned. Measurements on higher floors are influenced by the dynamic properties of building or structure, and as such prone to amplification inside the building or structure.

7.5 Restriction on access to buildings often make it necessary for measurements to be made outdoors or at a measurement point other than where the vibration effects are experienced. In such cases, an appropriate transfer function should be used to convert levels at the measurement point to those likely to occur at the assessment point inside the building. Where practical, testing should be carried out or results of existing studies should be used to determine the appropriate transfer function.

As a screening method, if the vibration limits as measured on the ground outside it could be assumed that the vibration levels would probably be met inside the building, for which no further work would normally be required for environmental impact assessment.

7.6 In addition to monitoring at sensitive receptors, vibration monitoring shall also be undertaken at critical receptors such as utilities and infrastructure facilities as well as other engineering structures with potential structural integrity concerns. These include mains water pipes, electrical and telecommunication cables, gas pipes, electricity sub-stations, etc.

These are often encountered in construction works where piling and excavation works are undertaken in vicinity of existing utilities and infrastructure installations.

The critical receptors shall be identified from site inspections.

8.0 VIBRATION SOURCES TO BE MEASURED

8.1 External sources vibration in the environment include but are not limited to:

- Construction (machinery, piling, work activities)
- Blasting (quarries, tunnel rock breaking)
- Transportation (road traffic, trains)
- Industrial (machinery, forging press)
- Others (low frequency sound from industrial plants).

8.2 Vibration in buildings may also occur from internal sources within the building structure. These include but are not limited to:

- Mechanical vibration sources in buildings (pumps, ventilation fans, cooling towers, chillers, gensets, industrial machines)
- Driveway and roads forming part of the building structure
- Wind (building and tower sway).

8.3 The most common sources of ground vibration in that often have to be measured over extended period of time either continuously or repeatedly over regular periods are construction activities from piling, rock breaking, tunneling, excavation, mechanized work process and heavy vehicles.

8.4 Piling in vicinity of sensitive locations require measurements to be undertaken over the entire duration of the piling. The measurements shall in principle accompany the piling machine wherever the piling works are carried out, and measurements undertaken at the closest sensitive receptors. In a linear project (highways and railways) the monitoring of the piling activities shall be along the entire alignment where sensitive receptors are located. Piling vibrations shall be continuously measured and reported.

8.5 Blasting, unless otherwise undertaken in remote areas, shall require vibration monitoring for every blasting events.

8.6 Measurements of road traffic and railways induced vibrations are to be undertaken as and when required for environmental impact assessment and project completion.

8.7 Measurements of industrial machinery and industrial sites are also undertaken as and when required for environmental impact assessment and compliance validation.

8.8 Measurements of vibrations of building vibrations originating from mechanical equipment and mechanized work process are often required for assessment and noise & vibration control. This shall include industrial plant and machinery in flatted factories and mixed tenancy buildings.

9.0 VIBRATION SEVERITY AND ASSESSMENT

9.1 Vibration levels are best determined by vibration measurements at the receptors of concern in the presence of the vibration sources and at that time of vibration events to determine the vibration levels.

Where appropriate, vibration frequency spectrum shall also be measured for information relating to vibration forcing frequencies and frequency response to be obtained.

Recommended procedures for vibration measurements are described in Annex B.

9.2 For projects, and other situations where a future potential vibration is to be assessed (i.e., before the physical occurrence of the vibration), it may be necessary to predict the likely vibration levels by calculations based on information of the vibration source(s) and the proximity of the source(s) to receptors of concern.

General guidance on procedures for the predictions of vibration propagation in the environment are described in Annex C.

While the procedures described are based on established and proven methods suitable for environmental impact assessment and general usage (based on international Standards, guidelines and best practice), it is recommended that additional guidance from applications specific international Standards and technical manuals to be included where appropriate.

9.3 Vibration severity can then be assessed based on the vibration levels (measured or predicted as the case may be) as propagated to receptors of concern.

The vibration levels shall be assessed against limits of the different criterion stated in Schedules of Recommended Vibration Limits. The assessment is in principle a quantitative assessment of measured (or predicted) level against the prescribed limits based on the different building types and functionality.

In addition to the above, assessment for potential disturbance may also require the vibration levels to be assessed against prevailing levels in the absence of the offending vibration source based on the incremental change in levels.

9.4 Groundborne vibration propagated in the environment and within buildings are typically assessed for:

(i) Potential structural damage.
(ii) Effects on human (human response ranging from motion sickness to annoyance).
(iii) Effects on vibration sensitive equipment.

9.5 Additional guidance on the evaluation of human exposure to vibration in buildings are given in BS 6472-1:2008 (for vibration sources other than blasting), BS 6472-2:2008 (for blast-induced vibrations), and BS ISO 4866:2010 (vibrations and evaluation of effects on buildings).

Recommended limits in this DOE Guidelines were based on guidance of BS 6472 (and other international standards and best practice) for human response and damage criterion.

9.6 Description of damage used in describing structural damage in buildings are in accordance with descriptors used in international standards (ISO 4866:2010) are:

(i) Cosmetic damage
(ii) Minor damage
(iii) Major damage.

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

Minor damage is defined as the *formation of large cracks or loosening and falling of plaster or wall surfaces, or cracks through bricks/concrete blocks*. There may not necessarily be a loss in the utility value of the load bearing structural members.

Major damage is defined as *damage to structural elements of the structure, cracks in support columns, loosening of joints, splaying of masonry cracks, etc.* There is a loss in utility value (reduction in load carrying capacity) of structural members.

The description of damage has its equivalent in the intensity scales used by seismologists.

9.7 Guidance on the evaluation and measurement for vibration in buildings with respect to damage from groundborne vibration are given in BS 7385-2:1993 and ISO 4866:2010. Another commonly used standards are DIN 4150-3:2016.

Limits used for damage threshold given in in this DOE Guidelines are based on recommendation of these Standards.

9.8 BS 7385-2:1993, Annex A (Cracking in Buildings) state that *cracks in buildings can occur immediately after construction or over a period of several years, depending upon the methods and material used in construction and change in ground characteristics. Heat, moisture, settlement, occupational loads, prestressing forces, material creep and chemical changes all cause movements in the building. Cracks normally exist to varying degrees in buildings not subjected to vibration and are not thus, in themselves, an indication of vibration-induced damage*.

Wall or ceiling lining materials and connections between masonry and wall elements with columns and beams rather than the main building components are often the most sensitive to imposed vibrations. For cracking to occur, the vibration induced strain combines with the pre-existing strain so that the critical strain of the wall covering material is exceeded.

9.9 In the event of vibrations had resulted or anticipated to result in minor or major damage, further investigations that include the determination and evaluation of stresses in building structural members shall be undertaken. This shall include structural integrity monitoring. The immediate reduction or removal of the vibration generation or origin at source shall be necessary.

9.10 Vibration levels below cosmetic damage limits, while structurally safe, when above threshold of human perception is still perceptible. Under such circumstances the vibration is related to human response and/or may be assessed against disturbance or annoyance.

10.0 VIBRATION AND PLANNING

10.1 The impact of vibration shall be considered in the planning of a project development; and in general, be guided by this Guidelines.

For the purpose of the consideration of vibration in planning, the following information may reasonably require and involve:

(i) identifying sensitive receptors that may be affected by the project development covering construction works and operation of the project.
(ii) determining the existing vibration levels in the community, including identification of existing sources of vibration generation.
(iii) identifying and assessing new sources of vibration which may affect sensitive and critical receptors in the project.
(iv) identifying vibration mitigation measures that may be required.

10.2 The Project Proponent and any other Person(s) who operate or cause to operate equipment, plant, process or activity with vibration generation shall undertake all reasonable measures to control the source of, or limit exposure to vibration. Such measures should be proportionate and reasonable, and may include one or combination of the following:

(i) Layout: adequate distance between vibration sources with sensitive receptors, buildings, facilities and utilities and infrastructure. The usage and designation of buffer zones shall be in accordance with guidelines issued by the Department of Environment from time to time.

(ii) Engineering measures: reduction of vibration at source with use of alternative methods, equipment or work process, reduction of impactive activities, isolation of vibration generated, and mitigation of groundborne and structure borne propagation by engineering measures.

(iii) Administrative measures: limiting the operating time of vibration sources; restricting the activities and ensuring acceptable vibration generated.

10.3 The Project Proponent and/or parties who undertakes construction, piling, drilling, excavation, demolition works, blasting and other construction related activities shall be required to inform the local authority and affected receptors in good time the nature of the proposed works and method statements to ensure that excessive vibrations are not generated.

10.4 Person(s) responsible for the development, construction and operations of highways and railways should undertake all reasonable precautionary mitigation measures such that groundborne vibrations propagated to adjacent buildings do not exceed acceptable levels.

10.5 Selecting an appropriate strategy for a proposed development, project or alterations to an existing development involves the following steps:

(i) Determine the vibration mitigation required to achieve the recommended vibration values.

(ii) Identify any project-specific or site-specific constraints and opportunities.

(iii) Investigate mitigation strategies adopted by similar industries or projects on similar sites.

(iv) Consider the range of mitigation options available.

(v) Consider community preferences for particular strategies. This is especially important when the community has particular sensitivities to vibration. This may include public engagements with affected receptors and Stakeholders to minimize complaints and manage expectations.

(vi) Undertake dilapidation surveys prior to, during and after construction or demolition works, in addition to vibration monitoring in determining conditions of buildings of concern, and the severity of vibration propagation from such works.

11.0 VIBRATION MAPPING

11.1 Vibration mapping may be required in projects to demonstrate the extent of groundborne vibration propagation over a relatively large land area - for example over distances more than 100 meters affecting an entire community. Typical situations include but not limited to ground vibrations originating from blasting and tunnelling works (using drill and blast methods, and tunnel boring machines in sensitive locations).

11.2 The main use of a vibration map is to provide visual information on areas and/or receptors located within the designated influence of the vibration generating works (typically blasting, rock-breaking and civil construction works). Vibration maps can also be used to evaluate the reasonability of complaints in vicinity of construction sites.

11.3 The vibration maps are plotted based on equipotential lines of vibration amplitudes, usually vibration amplitudes at limits of concern (for example 0.5mm/s, 1 mm/s, 2 mm/s, 5 mm/s ppv).

The vibration maps would show vibration levels (predicted or measured) for a range of different vibration generation conditions for example blasting due to variations in explosive quantities used (maximum instantaneous charge per delay), and locations blasting events. An example is shown in Plate 11-1 for blasting induced vibrations for a specific blasting situation from operational quarries propagated to existing and proposed new residential developments.

Plate 11-1: Vibration map showing predicted ground vibration contours from blasting site.

11.4 Vibration mapping for a project is usually not required in situations where the vibration propagated to receptors are within recommended limits at relatively short distances (for example 25m or 50m). In such situation, determination of critical distances corresponding to key vibration levels or limits are more useful. Receptors that are within critical distances could readily be identified from a screening exercise based on critical distances corresponding to acceptance limits.

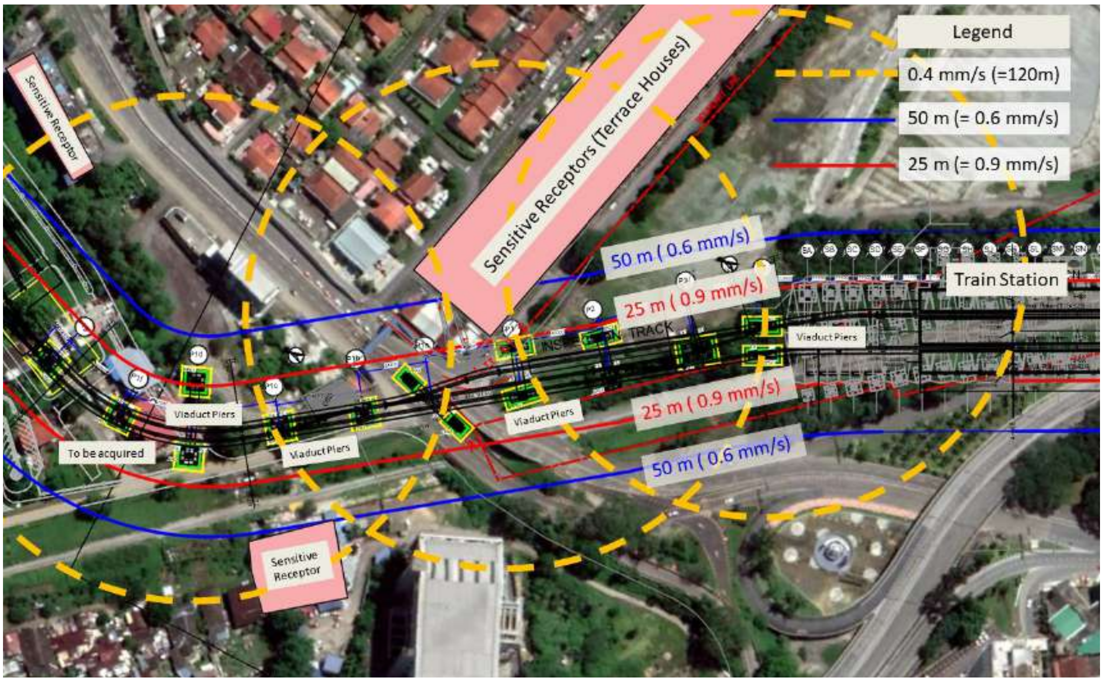

Plate 11-2: Vibration map showing predicted ground vibration zone of influence from piling locations for different critical distances and corresponding levels.

11.5 Zone of influence based on distances corresponding to different vibration levels perceived from the vibration source(s) can be plotted to visually demonstrate the extent of potential concern at sensitive receptors in proximity to the source(s).

An example is shown in Plate 11-2 for typical pile driving located in proximity to receptors from the viaduct piers and train Station construction site of an urban railway project. The example showed limited number receptors that were predicted to have vibrations exceeding day time limit (0.8mm/s) but a significantly larger number of receptors may be affected based on the night time limit (0.4mm/s). This would dictate that piling works to be done during daytime only.

11.6 In linear projects, representative typical plots demonstrating extent of problem to selected receptors may be sufficient instead of plots to all probable receptors along the entire alignment. The affected receptors along the entire alignment could be readily identified from critical distances screening exercise (without the need of vibration maps for each receptor location).

11.7 Groundborne vibration plots can be a useful tool for diagnosis, evaluation, qualification, and quantification of the effects of vibration used in conjunction of noise contours for a comprehensive noise and vibration assessment.

12.0 VIBRATION WORK SCOPE IN ENVIRONMENT IMPACT ASSESSMENT

12.1 This Section of the guidelines presents specific guidance on requirements to be considered and the work scope to be undertaken for vibration in an Environmental Impact Assessment (EIA).

12.2 The major items that shall be included in the EIA for noise are:

- Identification of sensitive and/or critical receptors.
- Establishing vibration acceptance criteria.
- Baseline vibration monitoring.
- Vibration predictions.
- Vibration impact assessment.
- Vibration mitigation; and
- Environmental Management Plan requirements.

The vibration predictions, impact assessment and mitigation shall cover:

- Construction (and demolition works where applicable).
- Operations; and
- De-commissioning works, where appropriate.

12.3 For industrial projects and other projects within a specific site, the assessment shall be at the project site property boundary and nearby / nearest residential and other sensitive receptors.

For infrastructure projects (often referred as linear projects such as highways, railways and transit trains), the assessment shall cover the entire alignment with emphasis to all developed or populated areas along the alignment corridor (typically up to 100m of alignment).

12.4 Circumstances which could lead to potential problems and significant residual impact on sensitive receptors that should be addressed in the vibration assessment include:

- Construction vibration which are often deemed prevalent and other likely source(s) of vibration concern to nearby receptors.

- Close proximity of the alignment (typically less than 100 m from receptors to construction sites) for infrastructure projects.

- Close proximity of vibration & noise sources and/or high vibration generation from plants and machinery for industrial and petrochemical projects.

12.5 Intent and Expectations of Vibration Assessment in an EIA Project

The assessment shall identify vibration sources and establish impacts of vibration generated during the construction and operation phase of the project. The assessment shall include review and mitigation measures that may be required to minimize adverse vibration impact form the project.

Baseline monitoring shall be required at identified sensitive receptors to establish prevailing vibration levels and identify any pre-existing vibration sources.

Vibration computational modelling and/or calculations shall be required to determine likely values of vibration generated from construction and operational vibration sources. In construction works, the vibration predictions shall include piling, blasting and tunnelling works where appropriate. Quantitative comparison of alternative piling, rock breaking and tunneling works shall also be undertaken where applicable.

Mitigation measures for vibration shall be reviewed and proposed.

The mitigation measures identified in the EIA are conceptual in nature that shall be subject to detailed design during project implementation. Mitigation measures may be subject to review in accordance with EIA Approval Conditions.

12.6 Work Scope for Vibration Assessment in an EIA Project

The following describe tasks that should be undertaken for vibration aspects in an EIA. The list is not necessarily exhaustive and should be refined to suit the project on a case by case basis. Some of the tasks described are also applicable only to certain projects type.

(i) To review project description, site and project drawings and relevant project design documents to obtain all necessary information relating to works that shall be undertaken in the EIA. The review shall include construction methods and work process to identify high vibration sources and activities.

(ii) To undertake site inspection(s) at the project site to identify vibration sensitive receptors and critical facilities, utilities and infrastructure at the project site. This shall initially involve review of aerial photographs, site plans to be followed by physical site inspection(s).

(iii) To undertake baseline vibration measurement at locations where the existing environment need to be established. This usually involves measurements at locations and areas with potential concerns.

(iv) Based on the receptors type and land use, review and propose vibration acceptance limits for project impact assessment.

(v) Where appropriate, undertake vibration testing to determine transfer function of ground vibration propagation at the project site, or representative alternative site with similar geological conditions. The test may include vibration measurements under controlled conditions for specific vibration source, drop hammer test, or from road traffic induced vibrations. Measurements shall be undertaken using multi-channel analyser to measure vibration levels simultaneously at different locations to determine scale distance relationships.

(vi) For blasting induced vibrations, measurements of controlled test trial blasting or from existing blasting to determine scaled distance relationships for vibration predictions.

(vii) Undertake vibration computations to determine likely levels of vibrations from construction activities and other vibration sources during project construction and operations.

(viii) Calculations in principle shall be undertaken using groundborne vibration propagation equations in accordance with the vibration source and extent of vibration concern (scale of project, type of project, extent of affected locations, etc.)

(ix) Vibration maps showing predicted vibration levels from the vibration source shall be prepared where appropriate. This vibration mapping is typically required in situations where the vibration propagation occurs over a relatively large area and long distances (more than 100m) such as blasting and tunnelling works.

(x) In construction sites and in generic situations for vibration propagation from discrete vibration sources, determine critical distances from the work sites or vibration sources where vibration levels are predicted to be levels of potential concern.

(xi) Conduct assessment of the predicted vibration levels at sensitive locations in accordance with limits recommended in the DOE Vibration Guidelines.

(xii) To establish a list of sensitive receptors and critical receptors that are anticipated to be affected by the Project during construction and operations phases.

(xiii) To review and propose vibration mitigation measures during construction and operations.

(xiv) To propose monitoring requirements during construction in the Environmental Management Plan, and post construction monitoring for EIA limits compliance.

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13.0 VIBRATION MITIGATION

13.1 When the measured and/or predicted vibration values exceed the recommended limits, mitigation measures to meet the recommended value should be considered.

13.2 There are three main mitigation strategies for vibration control:

(a) controlling vibration at source
(b) controlling the transmission of vibration
(c) controlling vibration at the receptor.

Vibration is most expediently minimized by reducing the dynamic forces associated with the source or by isolation techniques. The source may be isolated from the ground or structure, thereby reducing its propagation to the receptor's buildings. The structure and buildings may also be isolated from vibration sources.

Additional guidance on vibration mitigation and examples are given in Annex E.

13.3 The Project Proponent, and/or person responsible for the construction or industrial sites, and/or person(s) responsible for the vibration should use the "best practical means" to minimise the vibration generation and reduce its propagation to the environment.

13.4 Excessive vibration generation is deemed to occur when vibration levels exceed recommended limits as prescribed in this Guidelines. "Best practical means" in the context of these Guidelines, in general should include but not limited to:

(i) the size, design and inherent operation characteristics of the device, plant, process or activity.
(ii) the adjustment of operational parameters including reduction of energy input (e.g., blow or cycle for piling, limiting the instantaneous charge of explosives) to limit the intensity of vibration generated.
(iii) the selection and usage of alternative methods with low vibration generation.
(iv) the provision of and appropriate use of vibration isolators, and attenuation dampers.
(v) the provision if necessary and appropriate use of vibration transmission structural breaks or trench.
(vi) the proper usage and adequate supervision of equipment operation and work process.
(vii) regular maintenance of plant and control equipment.

13.5 The actual values of building vibration induced by sources are dependent on the vibration characteristics of the source, ground conditions, building foundations and building construction materials and techniques.

13.6 In instances of excessive vibration severity, the Department of Environment at its discretion may make it mandatory for the Project Proponent and/or vibration source originator or person(s) responsible for the excessive vibration generation to institute measures for reducing vibration levels to comply with recommended limits as prescribed in this Guidelines.

14 GLOSSARY

"airblast" is a pressure wave that may be audible or inaudible that are generated when explosive energy during blasting in the form of gases escape from detonation either through the blast holes or through fractures in the rock or at the ground surface.

"**cosmetic damage**" means hairline cracks on wall surfaces or the growth of existing cracks in plaster on walls or at mortar joints. The damage is superficial (cosmetic) not affecting functionality of the building elements.

"**community**" means the body of people gathered or living in the same locality.

"**Impulsive vibration excitation**" is vibration which has a rapid build-up to a peak followed by a damped decay which may or may not involve several cycles of vibration and is generally associated with single event occurrence such as blasting and explosions.

"**local authority**" means the local planning authorities or agents of the State as defined in the Town and Country Planning Act, 1976 and such rules, regulations and by-laws made there under. For the purpose of these Regulations, this shall include City Halls, City Councils, Municipal Councils, Town Councils and District Councils.

"**major damage**" means serious weakening of the structure with large cracks, loosening of joints, splaying of masonry cracks, or shifting of foundations, bearing walls, or major settlement resulting in distortion or weakening of the superstructure.

"maximum instantaneous charge" is the maximum amount of explosive in kg on any one specific delay detonator in any one blast hole.

"minor damage" means formation of large cracks or loosening and falling of plaster or wall surfaces, or cracks through bricks/concrete blocks. There is insignificant damage to the structure and does not necessarily result in a reduction in load carrying capacity of structural members.

"**real property boundary**" means an imaginary line along the ground surface, and its vertical extension, which separates the real property owned by one person from that owned by another person, but not including intra-building real property divisions, as delineated in the land title appearing in the Certificate of Title.

"**residential area**" means a designated area as gazetted by the local authority for the purpose of human dwellings and residence.

"**short term vibration**" is a vibration which is impulsive or transient in nature but are repeated periodically (but not necessarily at equal time period) over a duration of time and is generally associated with repetitive impactive events such as piling and hammer blows.

"**steady state vibration**" is a vibration which continues uninterrupted for a period of time of assessment.

"**threshold damage**" means visible cracking in non-structural members such as partitions, facings and plaster walls.

"**vibration**" is an oscillatory motion of solid bodies of deterministic or random nature described by displacement, velocity, or acceleration with respect to a given reference point.

"ground vibration" is vibration propagated in the ground, sometimes referred as groundborne vibration.

"vibration acceleration" is the speed of vibration (rate of change of the vibration velocity). Vibration acceleration is measured in m/s^2 (m/s per second), or g (gravity constant).

"vibration displacement" is the amplitude (distance travelled) between the peaks of the oscillating motion (vibration). Vibration displacement is measured in millimeters, microns (0.001mm), or mils (one-thousandth of an inch, 0.001 inch)

"vibration velocity" is the rate of change (speed) in the oscillating motion. Velocity of vibration is measured in millimeters per second (mm/s) or inch per second (ips).

"vibration dose" is a parameter that combines the magnitude of vibration and the time for which it occurs.

"vibration frequency" is the number of times the vibrating object oscillates, or vibrates, per unit of time. It is often expressed as number of cycles per second (referred to as Hertz, Hz), or cycles per minute (CPM).

"vibration dose value *VDV*" is the cumulative measurement of the vibration levels received over an 8 hour or 16 hour period, used in assessing intermittent vibration.

"vibration perception threshold" means the minimum ground-or structure-borne vibrational motion necessary to cause a normal person to be aware of the vibration by such direct means as, but not limited, sensation by touch or visual observation of moving objects.

"**vibration sensitive area**" means area where the absence of vibration is deemed necessary for the functional usage of the space, with requirements for the vibration level to be significantly below the human vibration perception threshold. These spaces include but are not limited to hospitals, operating theatres, precision laboratories, residential dwellings.

"**vibration velocity v_i**" means the vectorial sum of the instantaneous values of the vibration velocity in the three axes (x, y, z). This is computed from $v_i = \sqrt{(v_x^2+v_y^2+v_z^2)}$.

"**x axis**" means the orthogonal axis in the forward-facing direction of a building or standing person.

"**y axis**" means the orthogonal axis in the transverse direction (at right angle to the x axis) of a building or standing person.

"**z axis**" means the orthogonal axis in the vertical direction (orthogonal to the floor plane containing the x and y axes) of a building or standing person.

SCHEDULES OF RECOMMENDED VIBRATION LEVELS

FIRST SCHEDULE

RECOMMENDED GENERIC VIBRATION CRITERIA FOR HUMAN OCCUPANCY AND SENSITIVE RECEPTORS

Criterion curve	Maximum velocity level*		Description of use
	µm/sec (RMS)	mm/sec (RMS)	
Workshop **R=8** **(ASHRAE J)**	800	0.8	Distinctly perceptible vibration. Appropriate to workshops and non-sensitive areas.
Office **R=4** **(ASHRAE I)**	400	0.4	Perceptible vibration. Appropriate to offices and non-sensitive areas.
Residential **R=2** **(ASHRAE H)**	200	0.2	Barely perceptible vibration. Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment and low power (to 20X) microscopes
Operating Theatre **R=1** **(ASHRAE F)**	100	0.1	Threshold of perception. Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
VC-A **R=0.5** **(ASHRAE E)**	50	0.05	No vibration felt. Adequate in most instances for optical microscopes to 100X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B **R=0.25** **(ASHRAE D)**	25	0.025	No vibration felt. Appropriate standard for optical microscopes to 1000X, inspection and lithography equipment to 3-microns line width (detail size)**.
VC-C **R=0.125** **(ASHRAE C)**	12.5	0.0125	No vibration. A good standard for most lithography and inspection equipment to 1-micron detail size**.
VC-D **R=0.0625** **(ASHRAE B)**	6	0.006	Suitable in most instances for the most demanding equipment** including electron microscopes (TEMs and SEMs) and E-Beam systems, operating to the limits of their capability.
VC-E **R=0.03125** **(ASHRAE A)**	3	0.003	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary measures.

Notes
*As measured in one-third octave bands of frequency over the frequency range 8 to 100 Hz.
**The detail size refers to the line widths for microelectronics fabrication, the particle (cell size for medical and pharmaceutical research, etc). The values given take into account observations that vibration requirements of equipment depend upon the detail size of the process.
Criterion curves (R and VC) for vibration spectral components (vertical direction) in one third octave frequency bands are defined in the charts shown in Chart 1.
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Source: A Design Guide for Footfall Induced Vibration of Structures. M R Wilford and P Young; The Concrete Centre, 2006

SECOND SCHEDULE

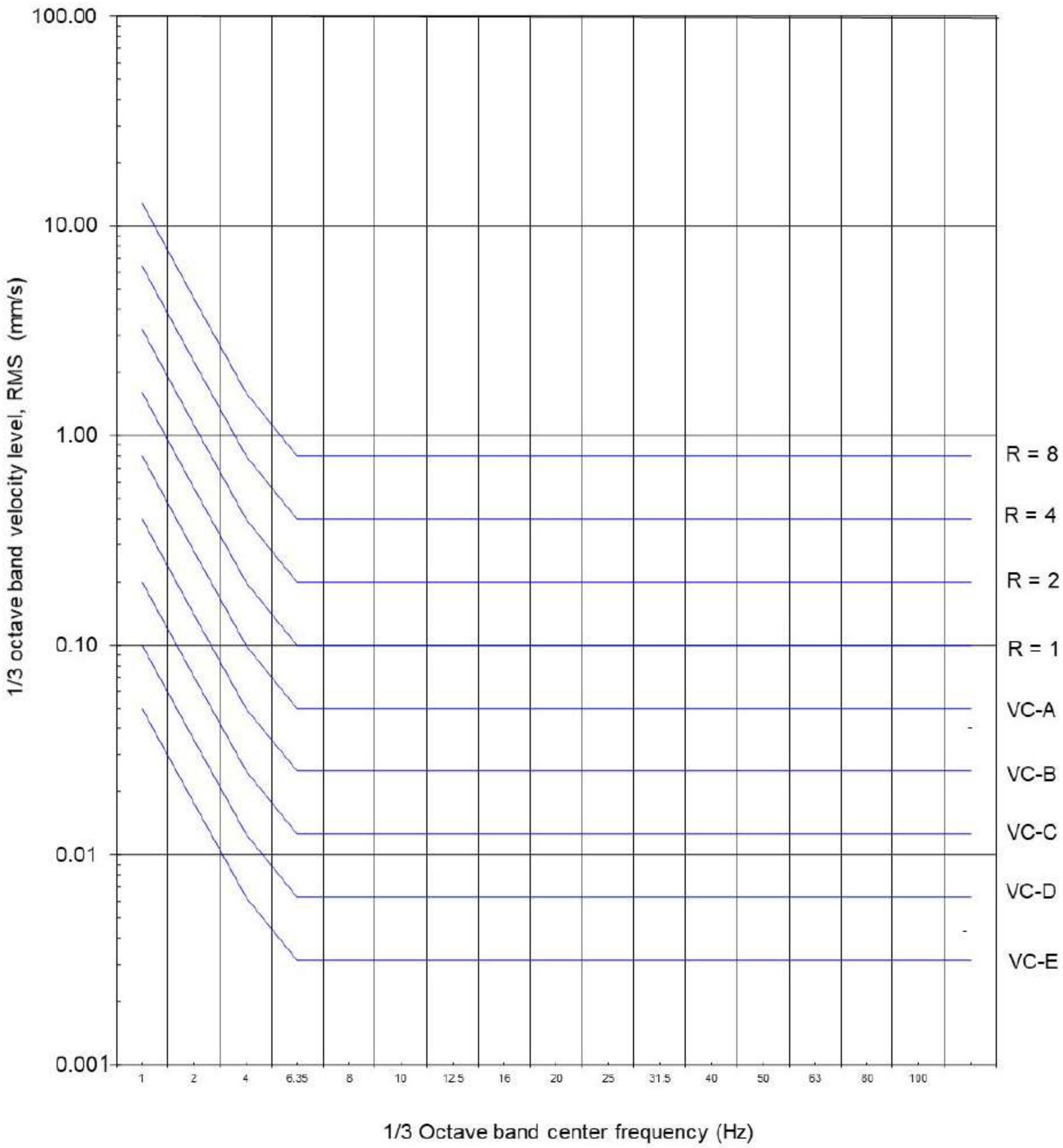
RECOMMENDED VIBRATION LIMITS FOR HUMAN RESPONSE AND ANNOYANCE FROM STEADY STATE CONTINUOUS VIBRATIONS

Receiving Land Use Category	Day Time 7.00 am - 10.00 pm	Night Time 10.00 pm - 7.00 am
Vibration Sensitive Facilities	0.1 mm/s (R=1)	0.1 mm/s (R=1)
Residential	0.2 mm/s to 0.4 mm/s (R=2 to R=4)	0.2 mm/s (R=2)
Commercial, Business	0.4 mm/s to 0.8mm/s (R=4 to R=8)	0.4 mm/s (R=4)
Industrial	0.8 mm/s to 1.6 mm/s (R=8 to R=16)	0.8 mm/s to 1.6 mm/s (R=8 to R=16)

THIRD SCHEDULE

RECOMMENDED VIBRATION LIMITS FOR HUMAN RESPONSE AND ANNOYANCE FROM INTERMITTENT VIBRATIONS

Receiving Land Use Category	Day Time 7.00 am - 10.00 pm	Night Time 10.00 pm - 7.00 am
Vibration Sensitive Facilities	0.1 mm/s (R=1)	0.1 mm/s (R=1)
Residential	0.8 mm/s to 1.6mm/s (R=8 to R=16)	0.4 mm/s (R=4)
Commercial, Business	1.6 mm/s (R=16)	1.6 mm/s (R=16)
Industrial	3.2 mm/s (R=32)	3.2 mm/s (R=32)



The criterion curve R=1 is based on the vibration perception threshold for human response (BS 6472 and ISO 2631). The designated numbers for other criterion curves are multiplying factors of R=1 (reference datum). For example, R=2 has a vibration 2 times of R=1, VC-A is half of R=1, and so on.

The R criterion curves are identical to the Rating Curves as used in the previous DOE Vibration Guidelines. R=1 is Curve 1, R=2 is Curve 2, R-=4 is Curve 4, etc.

Chart 1: Vibration Criterion Rating Curves

FOURTH SCHEDULE

VIBRATION DOSE VALUE RANGES WHICH MIGHT RESULT IN VARIOUS PROBABLITIES OF ADVERSE COMMENT WITHIN BUILDINGS

Receptors	Time period	Low probability of adverse comment VDV_b m·s$^{-1.75}$	Adverse comment possible VDV_b m·s$^{-1.75}$	Adverse comment probable VDV_b m·s$^{-1.75}$
Residential buildings	16 h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
	8 h night	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8
Office buildings	16 h day	0.4 to 0.8	0.8 to 1.6	1.6 to 3.2
	8 h night	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Workshop buildings	16 h day	0.8 to 1.6	1.6 to 3.2	3.2 to 6.4
	8 h night	0.4 to 0.8	0.8 to 1.6	1.6 to 3.2

Source: BS 6472-1:2008

Vibration dose value (***VDV***) is derived in accordance with Equation 1 (as defined therein BS 6472-1:2008) from the frequency weighted acceleration (in m/s^2) and total period of the day or night (in sec) during which vibration occur.

The vibration dose value (***VDV)*** is based on a weighted vibration acceleration level and takes into account the possible intermittent or varying nature of vibration. For vertical vibration, the weighting is based on curve W_b and the *VDV* determined according to this weighting is termed VDV_b.

The VDV_b value of 0.2 is equivalent to curve R=1 in the Schedule 2 and Schedule 3 above (with a slightly different weighting curve) and the value of 0.4 is equivalent to curve R=4.

FIFTH SCHEDULE

GUIDE VALUES FOR CONTINUOUS VIBRATION FOR COMESTIC DAMAGE

Building type	Limit Line [b]	Peak component particle velocity in frequency range of predominant pulse	
		4 Hz to 15 Hz	**15 Hz and above**
Reinforced or framed structures. Industrial and heavy commercial buildings	3	25 mm/s at 4 Hz and above	
Unreinforced or light framed structures. Residential or light commercial type buildings	4	7.5 mm/s at 4 Hz increasing to 10 mm/s at 15 Hz	10 mm/s at 15 Hz increasing to 25 mm/s at 40 Hz and above

Source: BS 7385-2:1993

Note a: Values referred to are at the base of the building.
Note b: Limit line are defined in Chart 2. For Line 4, at frequencies below 4 Hz, the maximum displacement shall not exceed 0.3 mm (zero to peak).

SIXTH SCHEDULE

GUIDE VALUES FOR INTERMITTENT VIBRATION RELATING TO COMESTIC DAMAGE

Building type	Limit Line [b]	Peak component particle velocity in frequency range of predominant pulse	
		4 Hz to 15 Hz	**15 Hz and above**
Reinforced or framed structures. Industrial and heavy commercial buildings	1	50 mm/s at 4 Hz and above	
Unreinforced or light framed structures. Residential or light commercial type buildings	2	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

Source: BS 7385-2:1993.

Note a: Values referred to are at the base of the building.
Note b: Limit line are defined in Chart 2. For Line 2, at frequencies below 4 Hz, the maximum displacement shall not exceed 0.6 mm (zero to peak).

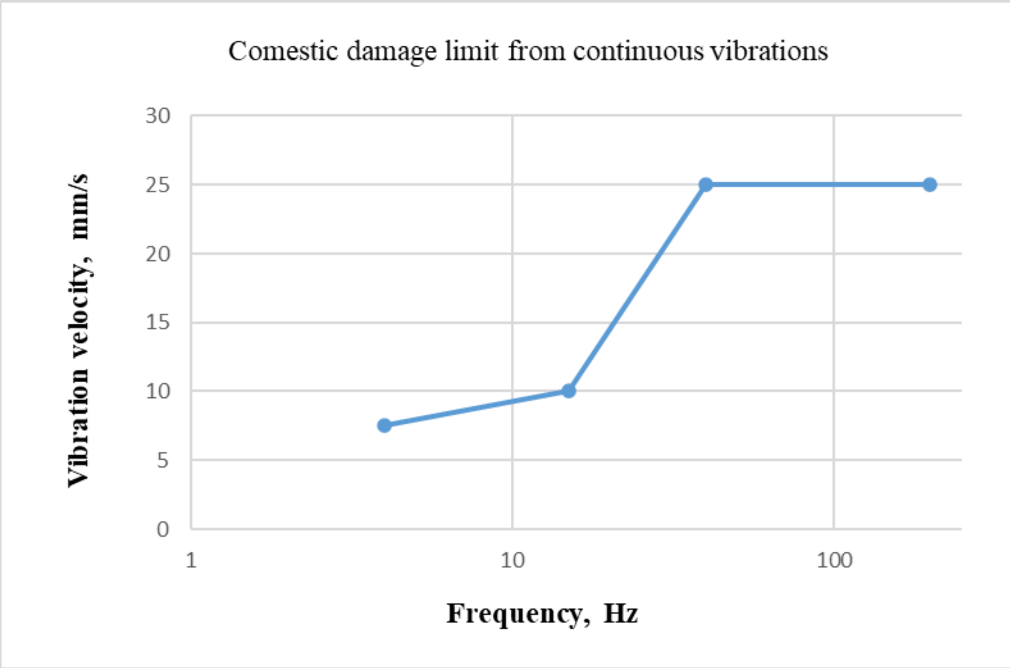


Chart 2: Continuous vibration guide values for cosmetic damage based on BS-7385-2:1993

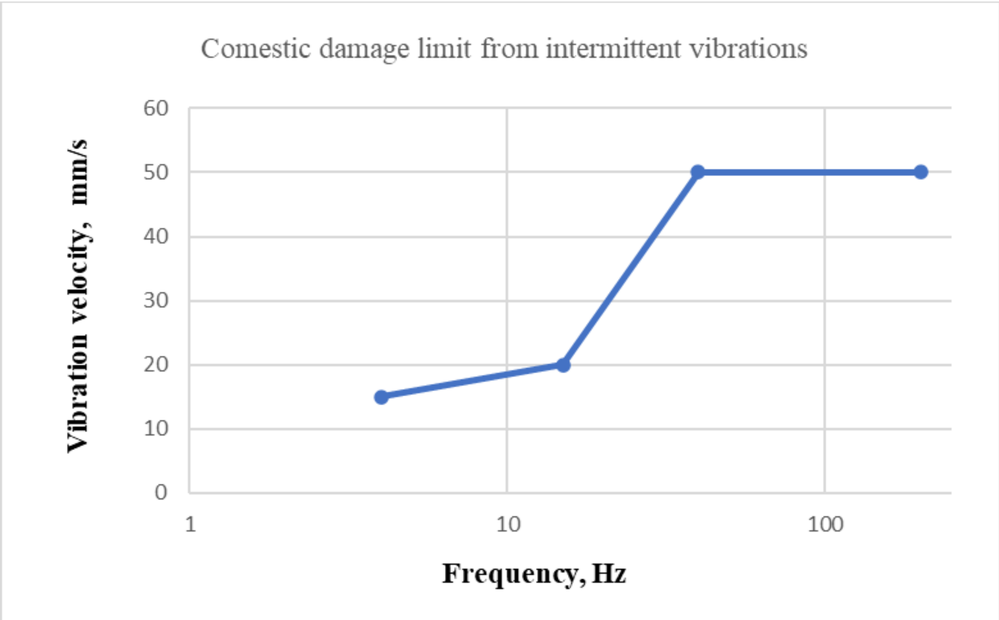
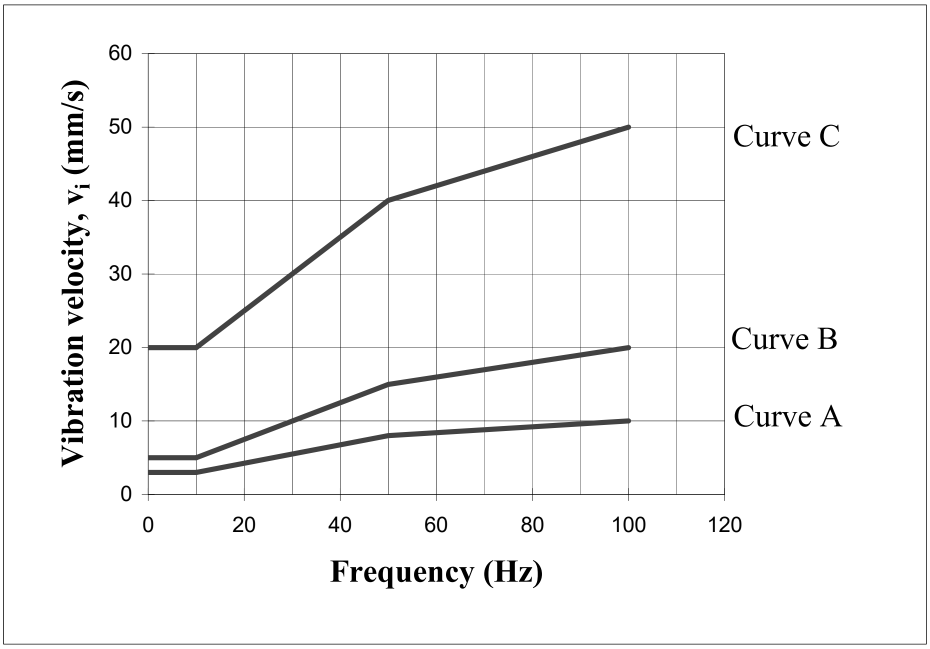


Chart 3: Intermittent vibration guide values for cosmetic damage based on BS-7385-2:1993



Source: DIN 4150-3:2016

Note 1: Vibration values for vectorial sum of vibration levels in three orthogonal axes on foundation

Note 2: Curve A= Vibration sensitive structures and buildings (residential houses, etc.)
Curve B= Commercial building, dwelling and buildings of similar design
Curve C= Industrial buildings and buildings of similar design.

Chart 4: Foundation vibration limiting values for cosmetic damage based on DIN 4150-3

SEVENTH SCHEDULE

RECOMMENDED VIBRATION LIMITS FOR HUMAN RESPONSE FROM SINGLE EVENT IMPULSIVE EXCITATION (NOT EXCEEDING 3 EVENTS PER DAY)

Receptors	**Time**	**Satisfactory magnitude peak particle velocity ppv**
Residential buildings	Day	5 mm/s
	Evening	4 mm/s
	Night	2 mm/s
Office buildings	Any time	5 mm/s*
Workshop buildings	Any time	5 mm/s*
Blasting #	**Airblast**	**Ground vibration**
Jabatan Mineral & Geosains Malaysia Limits	≤ 115 dBZ (Lin Peak)	≤ 5 mm/s ppv

Source: Adopted from BS 6472-2:2008 with amendments to suit Malaysian practice and Mineral Development (Blasting) Regulations 2013.

Note 1#: Blasting works undertaken in Malaysia are subjected to jurisdiction of the Minerals and Geoscience Department Malaysia [*Jabatan Mineral dan Geosains Malaysia* (JMG)] under the Mineral Development (Blasting) Regulations 2013. Limits imposed by JMG for blasting measured at blasting site boundary and/or nearest adjacent receptor. Any exceptions (for example limits applicable for 95% of all blasts) are subject to approval of JMG and/or Department of Environment on a case to case basis.

Note 2*: BS 6472-2:2008 have a relatively less stringent limit than values prescribed herein for office and workshops buildings. Limits prescribed herein rationalized against JMG Malaysia blasting vibration limits (5 mm/s ppv).

Note 3: Vibration measured inside buildings may be amplified by building resonance; and lower limits than values as tabulated above (based on BS 6472-2:2008) may be applied.

Note 4: When more than three impulsive events occur in a working day, the following relationship should be used to apply an additional multiplying factor, *F*, to reduce the above stated 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 sec, 0.32 for wooden floors and 1.22 for concrete floors.

EIGHTH SCHEDULE

GUIDANCE FOR VIBRATION LIMITS RELATING TO STRUCTURAL DAMAGE RISKS IN BUILDINGS FROM SINGLE EVENT IMPULSIVE EXCITATION (NOT EXCEEDING 3 EVENTS PER DAY)

Type of Structure	Ground Vibration Peak Particle Velocity mm/s		
	< 10 Hz	10 to 50 Hz	50 to 100 Hz
Residential buildings, dwellings, and buildings of similar design and/or use	5	5 to 15	15 to 20
Commercial building, industrial buildings, and buildings of similar design or use	20	20 to 40	40 to 50
Structures that, because of their sensitivity to vibration, do not correspond to those listed above, including heritage buildings	3	3 to 8	8 to 10

Source: DIN 4150-3: 2016

Note 1: Vibration thresholds for structural damage based on guidance values from DIN 4150-3:2016; measured at foundation.

Note 2: Vibrations from blasting are subjected to limits stipulated by Jabatan Mineral & Geosains Malaysia (JMG) of 5 mm/s ppv (measured at blasting site boundary).

NINETH SCHEDULE

GUIDANCE ON PERCEPTION OF VIBRATION LEVELS

Approximate vibration level* (Peak Particle Velocity)	Degree of perception
0.14 mm/s	Vibration might be perceptible in the most sensitive situations for most vibration frequencies associated with construction. At lower frequencies, people are less sensitive to vibration
0.3 mm/s	Vibration might just be perceptible in residential environments
1.0 mm/s	It is likely 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	Vibration is likely to be intolerable for any more than a very brief exposure to this level in most building environments.

Source: BS 5228-2:2009+A1:2014.

*Note: Magnitudes of values presented apply to a measurement position that is representative of the point of entry into the receptor. Single or infrequent occurrences of these levels do not necessarily correspond to the stated effect in every case. Values are given as an initial indication of potential effects.

ANNEX A

VIBRATION FUNDAMENTALS

1.0 Vibration motions

1.1 Vibration is an oscillating motion repeated over time that may be transit or repeated continuously with constant or varying amplitudes. Vibration in its simplest form is a simple harmonic motion and is shown in Figure A-1-1 below.

1.2 The amplitude of the waveform is described by the peak value, peak to peak, or root mean square (RMS) and average.

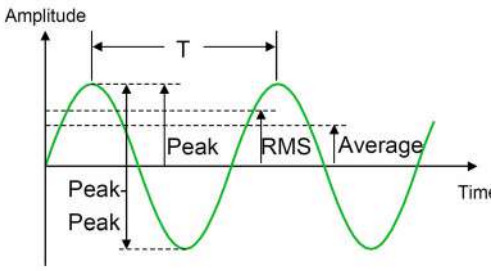


Figure A-2: Simple harmonic motion

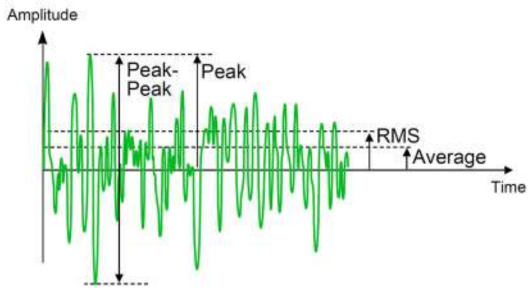


Figure A-2: Complex motion

1.3 Vibration propagated in the environment consists of complex waves (being the combination of many simple harmonic motions but with different frequencies, as shown in Figure A-1-2.

1.4 The mathematically expression of a simple motion (simple harmonic motion) is given by

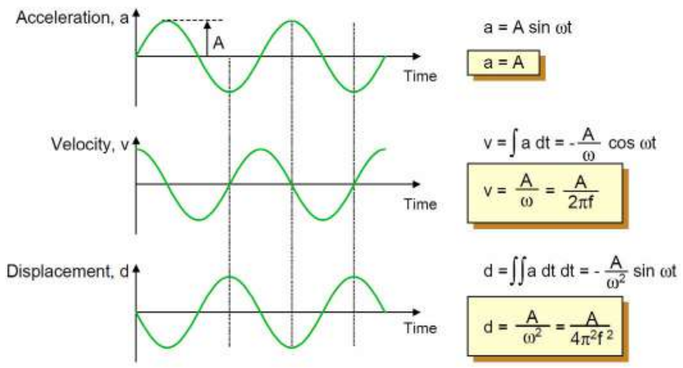
Displacement, $d = D \, Sin\,(\omega t)$
Velocity, $v = \omega D \, Cos\,(\omega t)$
Acceleration $a = -\,\omega^2 D \, Sin\,(\omega t)$

where,

d is the displacement at any given time,
D is the maximum amplitude (neutral position to its upper limit)
$Sin\,(\omega t)$, $Cos\,(\omega t)$ are the oscillation terms
ω is the frequency of the motion (rad/s)
$\omega = 2\pi f$ (Hz)

1.5 The practical significance of velocity relates to the cyclic changes of the motion per second, which affects fatigue life of the physical system. Velocity is used as a descriptor for vibration severity as it is a potential measure of fatigue life.

1.6 Acceleration is the change of velocity with time (i.e., how fast the speed (velocity) is changing). Physical significance of acceleration is it relates to inertia and is a measure of dynamic forces. The inter-dependence of force and acceleration is governed by relationship as shown in Figure A-2.



Source: Bruel & Kjaer

Figure A-2: Relationship between acceleration, velocity and displacement

1.7 The physical relationship between acceleration, velocity and displacement allows values to be converted between one another for a known frequency (f, Hz)

$V = A / (2 \pi f)$	$V = (2 \pi f) D$
$D = V / (2 \pi f)$	$A = (2 \pi f) V$
$D = A / (2 \pi f)^2$	$A = (2 \pi f)^2 D$

Care must be taken to ensure that correct units are used in the computations.

1.8 The time required for a complete cycle is referred to as the periodic time, T (seconds). In one cycle the number of cycles completed (cycle per second) is given by

$$\text{Cycle/sec} = 1/T$$

1.9 Vibration motion can be displayed in the time domain (amplitude vs time) of in the frequency domain (amplitude vs Frequency), as shown in Figure A-3.

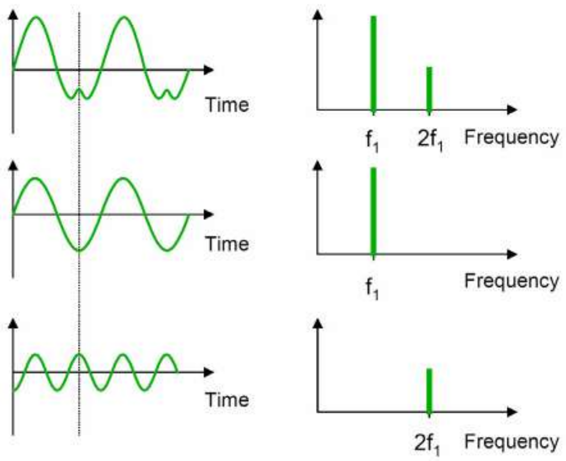


Figure A-3: Time domain and frequency domain

1.10 For environmental and building vibrations, frequencies of interest are from 1 Hz to 100 Hz. In machinery vibrations the range are typically from 1 Hz to 10 kHz.

2 Units of measurements

2.1 Common units of vibration measurements are:

Acceleration = m/s^2, G
Velocity = mm/s; inch/sec (ips) [1 ips = 25.4 mm/s]
Displacement = µm [1 micron = 0.001mm]; mil [1 mil = 0.001 inch].

2.2 A nomograph for conversion of vibration magnitudes conversion between acceleration, velocity and displacement at discrete frequencies is given below. With tow known parameters, the other two can be determined.

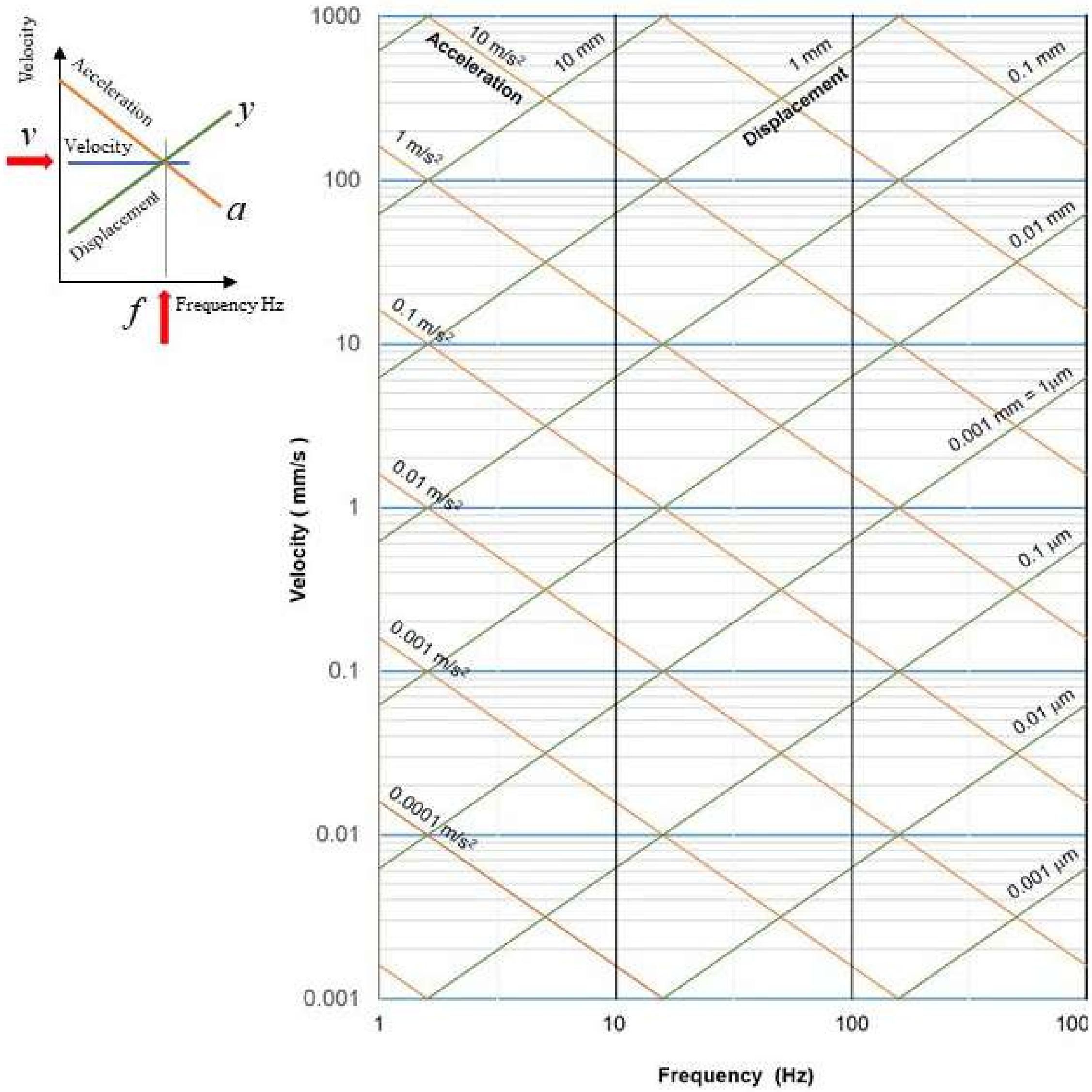


Chart A-1: Nomograph for conversion between acceleration, velocity and displacement at discrete frequencies

2.3 Vibration levels can also be expressed in VdB (velocity decibel) referenced to a specific reference level. The reference vibration level and units used must be clearly stated. The use of VdB is less common; and are sometimes used in older literature and rarely in international standards.

Vibration velocity level in decibels (VdB) is defined as

$$L_v = 20 \log(v / v_{ref})$$

where

v = velocity rms amplitude, mm/s

v_{ref} = 1×10^{-5} mm/s.

For imperial units

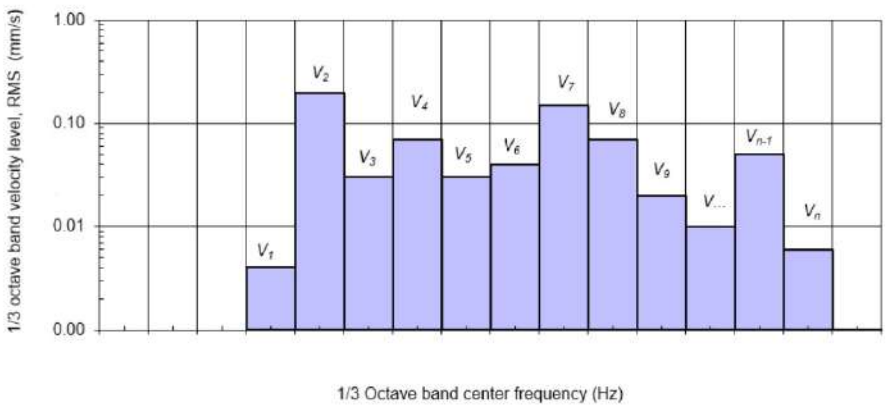
v = velocity rms amplitude, inch per sec

v_{ref} = 1×10^{-6} inch per sec (*1 inch/sec = 25.4 mm/s*).

As an example, a vibration velocity 5 mm/s = 114 VdB (ref. 10^{-5}mm/s).
In imperial units, the same vibration is 0.1969 ips = 106 VdB (ref. 10^{-6} ips).
Vibration velocity decibels VdB based on the imperial vibration reference level (ref. 10^{-6} ips) is numerically different with VdB based on SI units (ref. 10^{-5} mm/s).

2.4 Vibration time waveforms in practice are a combination of vibration with different frequency components (Figure A-2). The resultant overall vibration level is obtained from the summation (root mean squared values) of the vibration components corresponding to the different frequencies.

A typical plot of vibration frequency spectral components in one third octave center frequencies is shown below.



The overall amplitude is computed from the summation of the respective frequency components as follows

$$V_{overall} = \sqrt{v_1^2 + v_2^2 + v_3^2 + \cdots + v_n^2}$$

2.5 Example

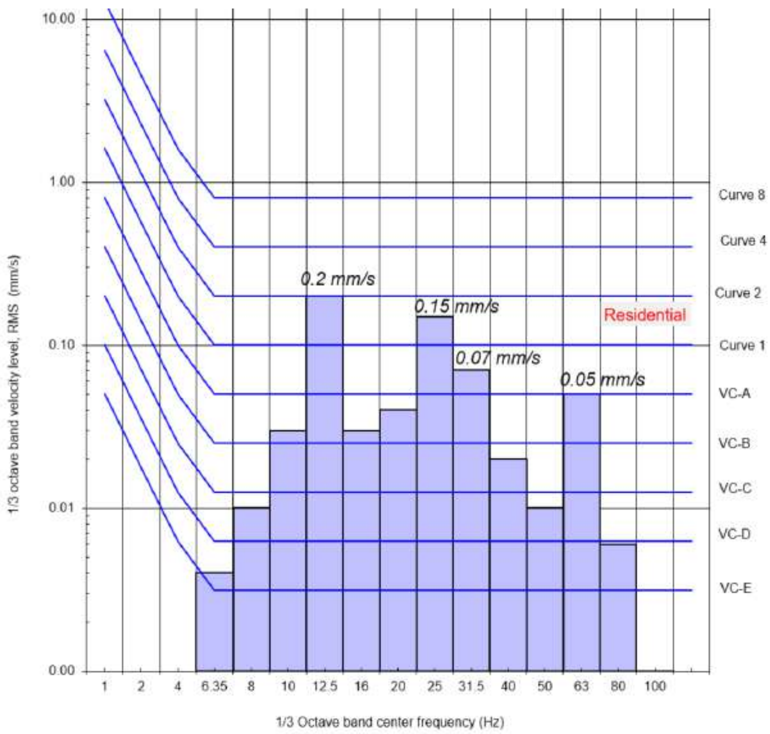


Figure A-4: Example of measured ground vibration in 1/3 octave band center frequencies plotted against rating curves

Frequency Hz	Velocity mm/s	Displacement* microns	Acceleration* m/s^2
6.3	0.004	0.101	0.0002
8	0.01	0.199	0.0005
10	0.03	0.477	0.0019
12.5	**0.2**	2.546	0.0157
16	0.03	0.298	0.0030
20	0.04	0.318	0.0050
25	**0.15**	0.955	0.0236
31.5	**0.07**	0.354	0.0139
40	0.02	0.080	0.0050
50	0.01	0.032	0.0031
63	**0.05**	0.126	0.0198
80	0.006	0.012	0.0030

*Displacement & acceleration values are to be computed based on the measured velocity values.

Figure A-4 shows a typical example of ground vibration measured on the building foundation with distinct mechanical forcing from mechanical plant room equipment. The measurements were undertaken in velocity (mm/s) and the values are as tabulated. The vibration frequency spectrum plot is as shown in the Figure.

(a) Determine the vibration rating curve for human response.
(b) Convert the measured vibration velocity values (mm/s) to displacement (microns) and acceleration (m/s^2)
(c) Determine also the overall vibration amplitudes in velocity, displacement and acceleration.

Frequency Hz	Velocity mm/s	Displacement microns	Acceleration m/s^2	Velocity Squared	Displacement Squared	Acceleration Squared
6.3	0.004	0.101	0.0002	0.000	0.010	0.0000
8	0.01	0.199	0.0005	0.000	0.040	0.0000
10	0.03	0.477	0.0019	0.001	0.228	0.0000
12.5	**0.2**	2.546	0.0157	0.040	6.483	0.0002
16	0.03	0.298	0.0030	0.001	0.089	0.0000
20	0.04	0.318	0.0050	0.002	0.101	0.0000
25	**0.15**	0.955	0.0236	0.023	0.912	0.0006
31.5	**0.07**	0.354	0.0139	0.005	0.125	0.0002
40	0.02	0.080	0.0050	0.000	0.006	0.0000
50	0.01	0.032	0.0031	0.000	0.001	0.0000
63	**0.05**	0.126	0.0198	0.003	0.016	0.0004
80	0.006	0.012	0.0030	0.000	0.000	0.0000
			Summation	0.074	8.011	0.0015
			Square Root	**0.272**	**2.830**	**0.0383**

a. The vibration rating curve is Curve R=2, which is suitable for residential receptors.

b. Conversion from velocity to displacement and acceleration has to be undertaken for each frequency based on the discrete value of each frequency.

For f = 6.3 Hz, D = V / (2 π f) = (0.004) / (2 π 6.3) = 0.000101 mm
= 0.000101 x 1000 = 0.101 micron
=0.101x1.414=0.14287 micron (0-Pk) = 0.1429x2=0.29 micron Pk-Pk

A = (2 π f) V = (2 π 6.3) 0.004 = 0.1584 mm/s^2
= 0.1584 /1000 m/s^2 = 0.0002 m/s^2

For f = 12.5 Hz, $D = V / (2 \pi f) = (0.2) / (2 \pi 12.5) = 0.002546$ mm
= 0.002546 x 1000 = 2.546 micron RMS
= 2.546x1.414= 3.6 micron (0-Pk) = 3.6x2=7.2micron Pk-Pk

$A = (2 \pi f) V = (2 \pi 12.5) 0.2 = 15.71$ mm/s^2
= 15.71 /1000 m/s^2 = 0.0157 m/s^2 RMS

For f = 25 Hz, $D = V / (2 \pi f) = (0.15) / (2 \pi 25) = 0.000955$ mm
= 0.000955 x 1000 = 0.955 micron RMS
= 0.955x1.414=1.35 micron (0-Pk) = 1.35x2 = 2.7micron Pk-Pk

$A = (2 \pi f) V = (2 \pi 25) 0.15 = 23.565$ mm/s^2
= 23.565 /1000 m/s^2 = 0.0236 m/s^2 RMS

The calculations are repeated for over frequencies using the corresponding vibration velocity and frequency values for each of the different frequencies. Representative computations for 6.3 Hz, 12.5 Hz and 25 Hz (highlighted items) are as demonstrated above.

Computed results for displacement and acceleration are each frequency are tabulated in the respective columns.

c. The overall amplitude is computed from the summation of the squared of the vibration component at each frequency as follows:

Overall $V_{overall} = \sqrt{v_1^2 + v_2^2 + v_3^2 + \cdots + v_n^2}$ vibration velocity amplitude is computed from the squared root of summation of component velocity squared as follows:

$V_{overall} = \sqrt{[0.004^2+0.01^2+0.03^2+0.2^2+0.03^2+0.04^2+0.15^2+0.07^2+0.02^2+0.01^2+0.05^2+0.006^2]}$

$= \sqrt{[0.074]} = 0.272$ mm/s RMS

$D = \sqrt{[0.101^2+0.199^2+0.477^2+2.546^2+0.298^2+0.318^2+0.955^2+0.354^2+0.08^2+0.032^2+0.126^2+0.012^2]}$

$= \sqrt{[8.011]} = 2.83$ microns RMS

$A = \sqrt{[0.0002^2+0.0005^2+0.0019^2+0.157^2+0.003^2+0.005^2+0.0236^2+0.0139^2+0.005^2+0.0031^2+0.0198^2+0.003^2]}$

$= \sqrt{[0.0015]} = 0.0383$ m/s^2 RMS = 38.3 mm/s^2 RMS

Tabulation of computations done in a spreadsheet is also shown.

ANNEX B
PROCEDURES FOR MEASUREMENT OF VIBRATION IN THE ENVIRONMENT

1.0 Measurement Equipment

1.1 Vibration measuring equipment shall consist of the following parts: a transducer or pick-up sensor, an amplifying device, level indicator and/or signal analyzer. Where appropriate, bandwidth filters should be included to limit the frequency range of the equipment and to apply the recommended filters to the input signal.

Instrumentation for environmental vibration is of the following generic types:

- Ground-borne vibration monitoring data loggers
- Dynamic vibration analyzers.

1.2 Vibration measurement may be conducted using either geophones (seismic velocity transducers) or accelerometers. A tri-axial transducer arrangement (i.e., either tri-axial geophones or accelerometers) is required for measurements in three axes (vertical, horizontal and transverse directions).

1.3 Other types of measurement equipment using different sensors technology such as strain gauges and lasers while in principle can be used for vibration measurements on buildings or structures are however not practical for groundborne vibrations and are more suitable for mechanical and structural vibration applications instead.

1.4 Vibration transducers shall be in compliance to IEC Publication 184, and auxiliary equipment (amplifiers, frequency selective equipment and carrier systems) in compliance to IEC Publication 222, or equivalent (ISEE or DIN 45669).

1.5 Vibration frequency analyzers or signal analyzers (of either type based on instrumentation hardware, or software digital signal processor) with one third octave filter sets or narrow band FFT (fast Fourier transform) bandwidth, shall be used for vibration frequency analysis (1 to 100 Hz minimum).

1.6 The vibration measurement system shall be designed specifically for continuous time recording, event recording (time history) or manually triggered. The vibration measurement system shall be come as a battery powered robust compact unit containing weatherproof digital recorder and communication with external 3 channels seismic sensor or accelerometer (for tri-axial measurements).

1.7 Instrumentation for single or multiple event impulsive vibration excitation monitoring and data recording with equivalent accuracy to vibration measurement equipment as stipulated herein may also be used. Such equipment shall be used in accordance with manufacturer’s instructions.

1.8 All vibration measuring equipment shall be properly calibrated in accordance with current standards and thereafter, or recommendations governing the calibration of such equipment in accordance with equipment manufacturer’s instructions.

2.0 Measurement locations

2.1 Measurements of vibration in general shall normally be taken on a building structure surface supporting a human body; and in instances of ground vibration or measurements at a real property boundary, may have to be made outside the structure, or on some surface other than points of entry to the human subject.

2.2 When measuring vibration at the foundation, the transducers for the three axes of vibration shall be placed close to one another in the lowest storey of the building under investigation, either on the foundation of the outer wall or in the outer wall, or in recesses in the outer wall.

For buildings having no basement, the point of measurement shall lie no more than 0.5 m above ground level. Measuring points shall preferably be located on the side of the building facing the source of excitation.

Vibration as a function of time shall be measured for the x, y and z directions, with one direction of measurement being parallel to one of the side walls of the building. In the case of buildings of large ground area, measurements shall be taken simultaneously at several points to record maximum vibration magnitude.

2.3 In addition to measurements taken at the foundation and to those at the uppermost storey, the vertical axis vibration of floors, where necessary measured approximately at the center of the floor area, shall be included in the evaluation.

2.4 When measuring the x and y axes vibration of the floor of the uppermost full storey, the transducers shall be placed in, or close to, the outer masonry. They shall be set up in the x and y directions; one direction of measurement shall be parallel to one of the side walls of the building.

2.5 The number of measurement positions will depend upon the size and complexity of the building. The number of buildings and/or receptors to be measured shall also depend on the extent of the project development, and/or zone of influence of the vibrations generated from vibration sources.

2.6 Measurement for blasting and other explosions related impulsive vibration excitation, if measured outside buildings, shall preferably be measured on a hard surface on ground as close to the property of interest or at real property boundary as the case may be. Transducers may be buried in the ground if no such hard surface is available.

2.7 It may be necessary to carry out measurements at several positions at regular distances apart from the vibration source to determine transfer function and ground damping for vibration predictions and assessment.

2.8 In situations where measurements at the foundation is not possible, or when measurements are carried out in open ground, transducers must be well coupled to the ground.

3.0 Measurement Type and Parameters

3.1 Building vibration, and measurements for assessment of human response and annoyance shall be measured in vibration velocity or acceleration terms. The recommended vibration limits as given in this Guidelines are based on vibration velocity.

3.2 Single event impulsive vibration excitation shall be measured in terms of peak particle velocity.

Peak particle velocity should preferably be measured simultaneously in the three orthogonal x, y, z axes: and the vectorial sum v_i computed based on the instantaneous values v_x, v_y, and v_z. When a multiple channel analyzer is not available, a conservative estimate of the vectorial sum v_i may be computed from single (or dual) channel measurements of v_x, v_y, and v_z. Such assumption should be reported accordingly.

3.3 The maximum value v_{max} is measured in a designated single direction and shall be in a direction normal to a wall or a particular plane of interest.

3.4 Real time frequency domain measurements (in one third octaves or narrow bandwidth) may be undertaken to obtain the vibration frequency spectrum for evaluation on the nature of the vibration forcing.

3.5 Measurements and/or data recording of unfiltered time histories of vibration may also be undertaken from which any desired data reduction for frequency analysis and the rms total value may be determined.

3.6 Vibration measurements shall be undertaken within a frequency range of 1 Hz to 100 Hz minimum.

(a) In the event of any occurrence of vibration response at frequency higher than 100 Hz, supplementary measurements up to at least the second harmonics of these higher order frequencies shall be undertaken.

(b) In the event that extraneous signal noise (such as cable or electrical noise) unrelated to the vibration measurement is deemed to influence the measurements, a high-pass filter with a value greater than 1 Hz but not more than 10 Hz may be used. In this instance the person undertaking the measurement and analysis must conclusively validate no vibration response components of significance up to this cut-off frequency of the high pass filter.

3.7 Measurements for steady state vibration shall be measured with peak or rms-weighted averaging over the duration of measurement period of interest, and with an averaging sample to obtain readings repeatable to 95% confidence limits.

3.8 Measurements for single event impulsive vibration excitation shall be measured on peak hold levels over the duration of measurement period of interest.

4.0 Duration of measurement

4.1 Measurements in general shall be undertaken over the duration of operation of the vibration source(s), process or activity which results in vibration generation to obtain a fair representation and record keeping of actual vibrations generated.

4.2 In instances of vibration monitoring for potential structure damage concern in buildings, and for compliance record keeping arising from construction, maintenance, demolition or excavation works, and blasting, the measurement shall be continuous for the entire duration of the vibration activities. A level vs time chart recording for the period is recommended.

Monitoring prior to the commencement of these activities is also required to establish typical prevailing vibration levels.

4.3 Short term measurements of not less than 30 minutes sampled over different time periods of the day for typical vibration events prevailing at the receptors intended for initial screening and determination of typical baseline vibration levels at receptors locations are acceptable assessment of prevailing conditions and human response. The sampling must however include period(s) of vibration generation activities that are prevailing at the receptors.

Short term measurements are not acceptable for monitoring of construction activities, and in particular piling and tunneling works.

4.4 Continuous monitoring over a complete 18-hour cycle may be required in the event that human annoyance and response are of concern from construction activities (day, evening and night). Continuous monitoring over 24 hours is also acceptable, although not necessary in most situations (for common vibration sources relating to road traffic and railways).

5.0 Calibration

5.1 Testing and recalibration of geophones, accelerometers and vibration measurement instrumentation shall be conducted by a calibration laboratory at intervals not exceeding 24 months.

5.2 The vibration monitoring system shall also be field calibrated using portable vibration calibrator or alternatively in the laboratory using a vibration shaker with a reference accelerometer.

6.0 Procedures

6.1 To ensure the vibration measurement accuracy, it is critical to maintain effective and secure coupling of the transducers to the ground, building foundations, other structural elements or substrates on which measurement is undertaken.

6.2 Measurement procedures shall be guided by the following guidelines and standards:

- Geophones: ISEE Field Practice Guidelines for Blasting Seismographs, 2009.
- Accelerometers: BS 5228-2: 2009+A1: 2014 or AS 2436-2010.

6.3 The preferred coupling method depends on site conditions. Where there is a rigid surface (e.g., concrete or bedrock), adhesive or mechanical bonding can be used. Where the surface is soil, the transducer can be embedded or fixed to an embedded mount (for example, 200 mm concrete cube or solid steel plate). If measurements are repeated at the same location, an embedded mount is particularly useful for consistency of results.

Coupling with soil spikes in soft conditions may lead to exaggerated measurements and is not recommended.

6.4 Baseline monitoring shall be undertaken before commencement of construction works, preferably within two (2) weeks of site possession to establish prevailing vibration levels from typical existing activities.

6.5 Frequency of monitoring for construction activities shall be continuously over the entire duration of piling to follow piling machines at the nearest receptor of concern.

7.0 Monitoring for Human Perception

7.1 Measurements for gauging human perception should be conducted to determine the resultant PPV and meet the following requirements:

7.2 Measurements on the ground should be representative of ground motions at the subject building or structure, but at sufficient distance from the building or structure to avoid undue interference from that structure.

7.3 Measurements within a structure should be located on the floor of the room where any complaint originates or where the greatest adverse impact is predicted. One or two measurement points in a suitable available area, preferably in the central part of the room is typically sufficient in most cases.

7.4 Measurement shall be conducted during construction activity for the duration of the piling activities.

8.0 Monitoring for Damage Assessment

8.1 Measurement for assessing structural damage and building contents shall be located at:

- Base / foundation of the structure.
- Horizontal plane of the highest floor of a structure, if required.
- Locations representative of sensitive building or infrastructure contents or building elements.

8.2 The monitoring shall be undertaken during construction activity for the entire duration of the piling. Shorter representative period (1 to 2 hours) may be undertaken to determine pre-construction exposure.

An example is shown in Plate B-5.

9.0 Blast Monitoring

9.1 Measurement for blasting induced vibrations may be undertaken using dedicated blasting vibration monitoring equipment (Blastmate or equivalent which are fitted with a microphone for simultaneous measurement of airblast overpressure, or multi-channel vibration data logger with triggering functions.

An example is shown in Plate B-7.

9.2 Tri-axial sensors are used to obtain the peak particle velocities in three orthogonal directions for ground vibration propagation in the three directions (P-waves, S-waves and R-waves).

Source: https://www.geonor.com; https://profund.nl; https://rion-sv.com

Plate B-1: Examples of vibration monitoring loggers with geophone sensor

Source: https://www.geosig.com

Plate B-2: Examples of vibration monitoring system with accelerometer sensor

Source: https://www.acoem.com

Plate B-3: Example of integrated vibration monitoring system (sensors integrated into module) come with mounting base plate

Plate B-4: Vibration monitoring unit with accelerometer sensor for measurement at work site

Plate B-5: Vibration monitoring unit with geophone sensor for measurement at receptor building

Plate B-6: Vibration monitoring unit (integrated sensor type) used for baseline measurement at residential location.

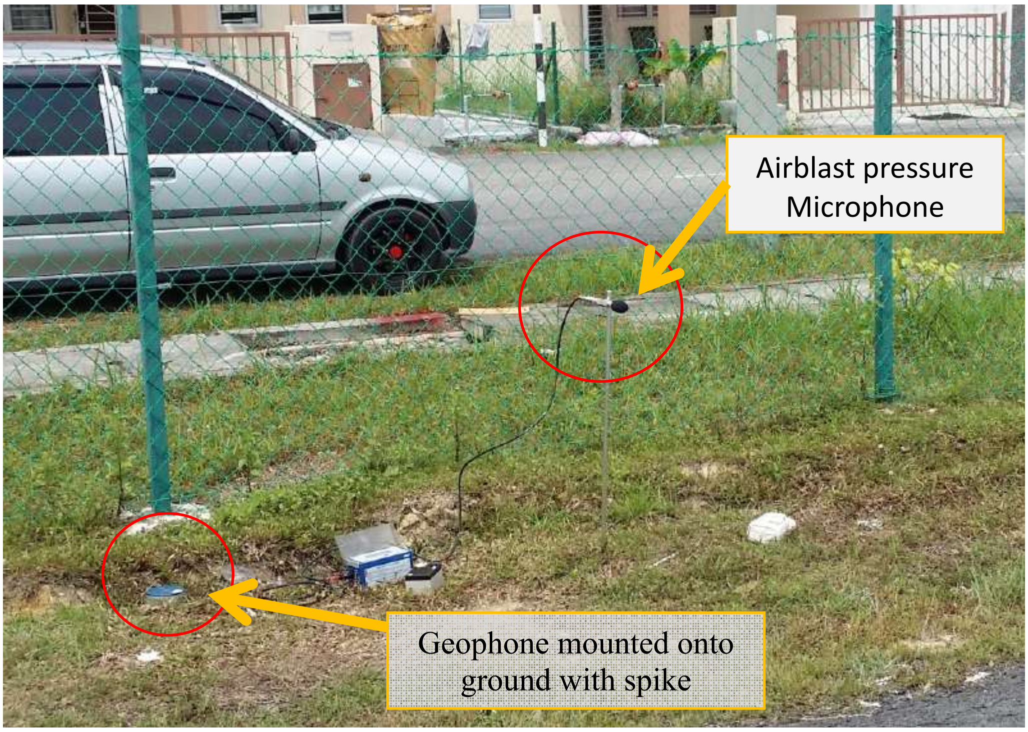


Plate B-7: Blasting vibration monitoring unit with airblast pressure microphone used ion quarry blasting measurement at adjacent residential location.

Plate B-8: Mounting plate with spikes for geophone sensor intended to be inserted onto ground.

Plate B-9: Mounting plate with bolt fasteners be secured onto hard surface (bolted onto floor slab)

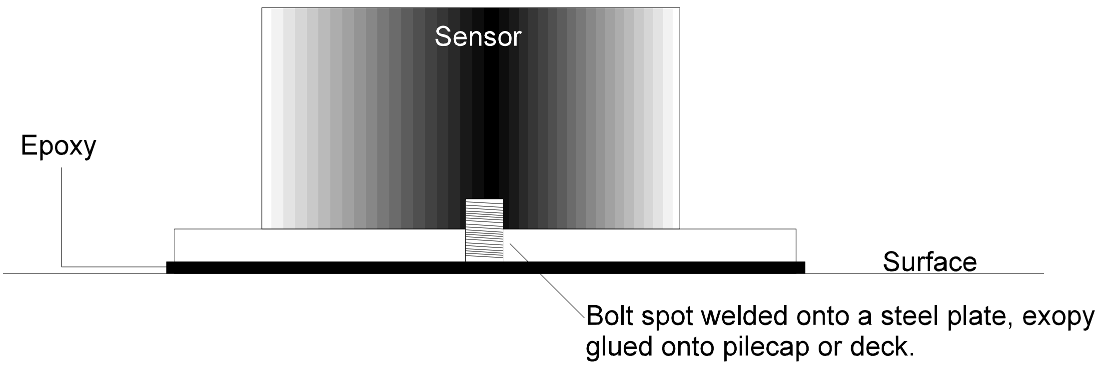


Plate B-10: Sensor bolted onto mounting plate that is to be secured onto hard ground surface with epoxy, or alternatively mounting plate to be spot welded onto surface (for steel structure or pile cap)

Plate B-11: Mounting plate (OEM accessory) for vibration monitoring system being bolted onto building structure for rigid coupling of equipment (built-in sensor) to building foundation

Plate B-12: Vibration monitoring unit and accelerometer sensors bolted onto ground beam at perimeter boundary of construction work site

Plate B-13: Vibration monitoring unit and geophone sensor being set up for measurement at construction work site. Geophone sensor rigidly secured onto solid surface with bolt threaded thru sensor body.

Plate B-14: Vibration sensor (piezoelectric type) with magnetic base secured onto steel washers bonded onto hard ground with epoxy for vibration transfer function testing

10.0 Do and Don’ts in Vibration Monitoring

10.1 Examples of recommended instruments and correct use of vibration measurement systems are given in Plates B-15 to B-8.

10.2 Plate B-1 shows the use of a mounting plate with spikes intended for monitoring location on soft ground, and mounting plate bonded onto hard ground with epoxy.

Plate B-2 shows the wrong use of the mounting plate with spikes for monitoring on hard ground (walkway) adjacent a construction work site. The vibration sensor on spikes was free to drift (wobble and detach from the ground) during any groundborne motions. This unacceptable practice would result in wrong readings as the sensor was not bonded onto the ground to correctly measure the ground vibrations.

Plate B-3 shows acceptable mounting of sensor on soft and hard ground surfaces. These examples were from baseline vibration monitoring and groundborne vibration testing at a construction work site.

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Plates B-4 to B-6 shows examples from monthly vibration monitoring at MRT work sites. As these measurements were at identical locations, the ground surface was prepared with inserts for bolting of the sensor and monitoring units onto the ground (ground beams, floor slabs, and edge of culvert).

Plates B-7 to B-8 shows unacceptable practice of placing the sensor onto the ground and “held” in place by gravity of a loose stone / rock.

Plate B-15: Vibration monitoring unit with geophone sensor set up at sensitive receptor adjacent construction works site (across the road).

NOT ACCEPTABLE

Plate B-16: Geophone sensor secured onto mounting plate with spikes and placed directly onto hard surface. Sensor with spikes will drift due to ground vibrations.

Plate B-17: Geophone sensor bolted directly onto hard surface (without using a mounting plate with spikes).

Plate B-18: Accelerometer sensor secured onto mounting plate bolted onto concrete slab

Plate B-19: Vibration monitoring undertaken at building foundation closest to column of receptor's building

Plate B-20: Vibration monitoring undertaken at construction site perimeter boundary with sensor rigidly coupled onto concrete pavement

Plate B-21: Vibration monitoring at receptor location by road side fronting piling vibrations at viaduct pier. *See close up view below*

NOT ACCEPTABLE

Plate B-22: Geophone sensor placed onto solid ground held in place with small rock.

Sensor should instead be stud fastened onto base plate and epoxy bonded onto ground.

Plate B-23: Vibration monitoring at receptor location by road side fronting adjacent construction site. See zoom view below

Plate B-24: Geophone sensor placed onto solid ground held in place with small rock. Sensor should instead be stud fastened onto base plate and epoxy bonded onto ground

Plate B-25: Vibration monitoring equipment secured onto solid ground beam at residential locations

Plate B-26: Use of integrated vibration monitoring equipment placed onto road surface avoid problems of rigid coupling of geophone sensor type monitoring equipment

11.0 Results to be Reported

11.1 Results to be reported can be in the form of singular numerical value of the vibration measured, typically overall vibration magnitudes (mm/s, m/s^2, or microns) or vibration time histories plots.

11.2 Chart B-1 show vibration velocity monitoring continuously monitored over the day evening period for piling vibrations. Results presented in magnitudes versus time over monitoring period. Another example showing monitoring measurements for vibration acceleration at another piling location is shown in Chart B-2.

11.3 Chart B-3 and Chart B-4 show vibration results reported using OEM reporting system with vibration levels plotted over monitoring period, and the human response assessed against ISO 2631 rating curves.

11.4 Results of unmanned continuous vibration monitoring should always be checked against construction activities (work log sheets) to verify high vibration events and to identify spurious results, if any. An example is given in Chart B-5 that showed high peaks that were suspected to be due to workers accidently hitting sensors.

11.5 In addition to vibration amplitudes plotted against time, vibration amplitudes (in one third octave center frequencies) can be plotted against ISO 2631 rating curves or DIN 4150 assessment charts.

Chart B-6 to Chart B-9 give examples of vibration levels plotted against ISO 2631 rating curves for human response for measured levels in three directions. The ISO human response rating curves for longitudinal and transvers directions are different from the vertical direction, and care should be taken to use the rating curves corresponding to the measurement directions.

11.6 Blasting result in impulsive vibrations, and the vibration time histories showing vibration decays are plotted simultaneously in the three measurement directions (vertical, longitudinal and transverse). An example is shown in Chart B-10.

The airblast overpressures from the blasting (measured in dBZ or dB Linear) are usually measured simultaneously with the vibrations. An example of typical results showing airblast overpressures and vibrations are given in Chart B-11.

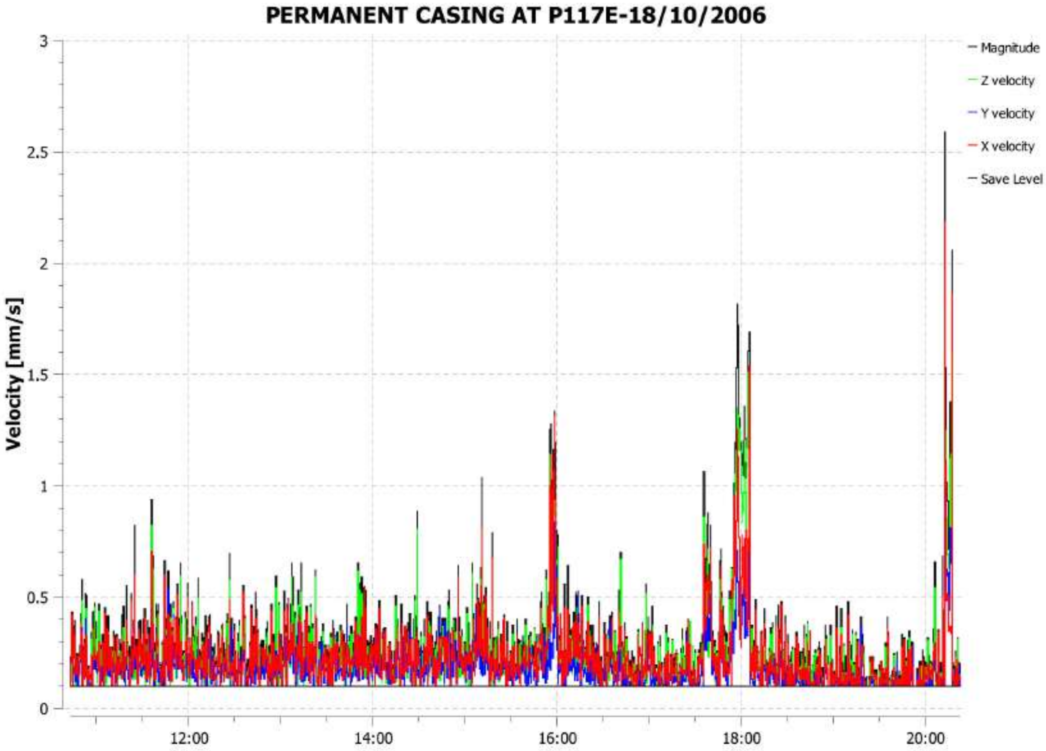


Chart B-1: Example of vibration continuous monitoring (reported in velocity ppv mm/s) for piling vibrations over working day and evening

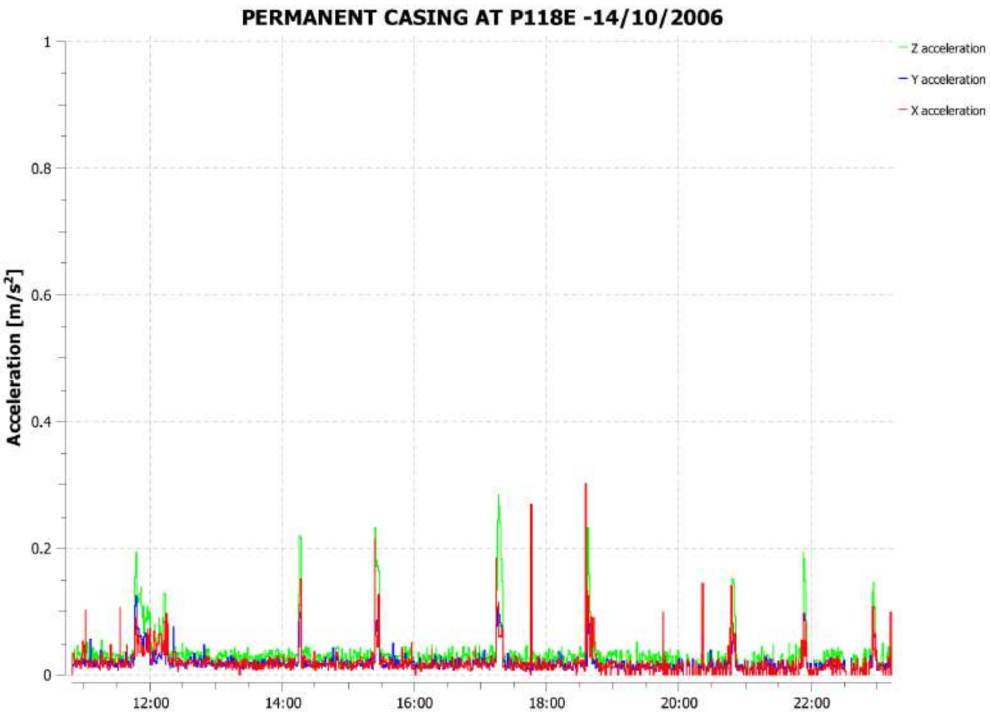


Chart B-2: Example of vibration continuous monitoring (reported in acceleration m/s^2) for piling vibrations over working day and evening

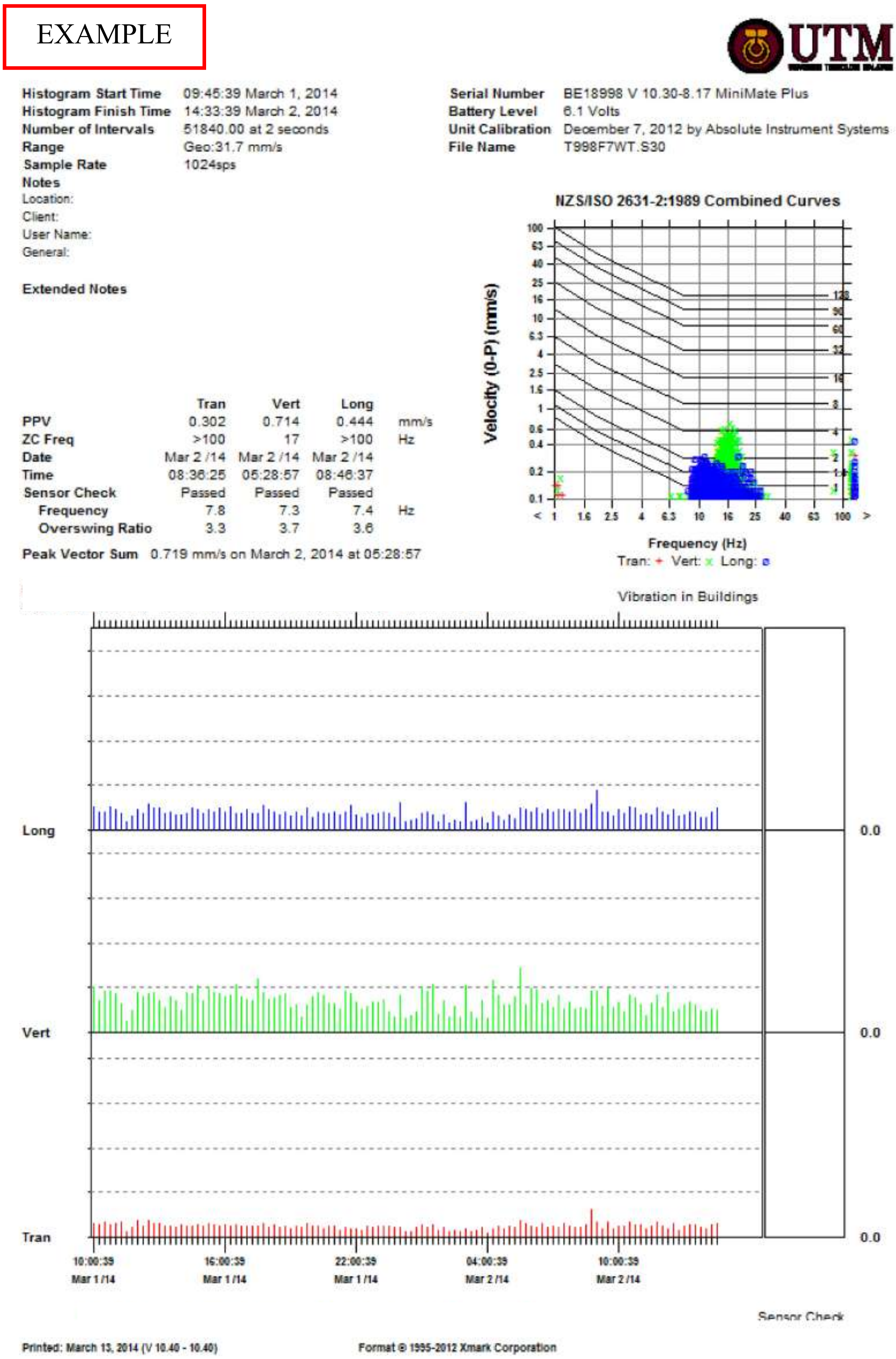


Chart B-3: Example of vibration continuous monitoring (reported in velocity ppv mm/s) at construction work site perimeter boundary.

Results presented in vibration levels vs time and plotted against ISO 2631 human response curves. Steady vibrations were observed

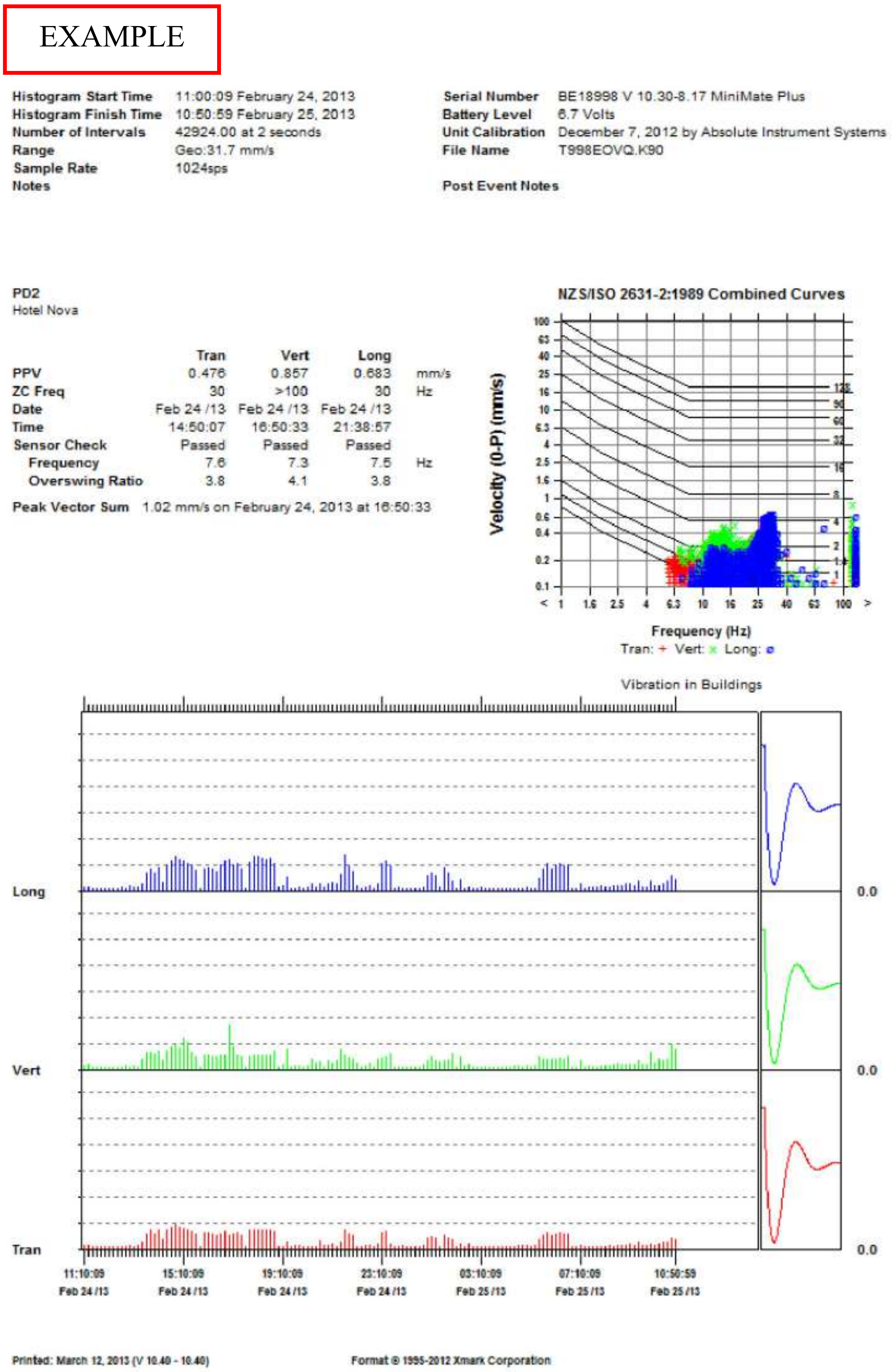
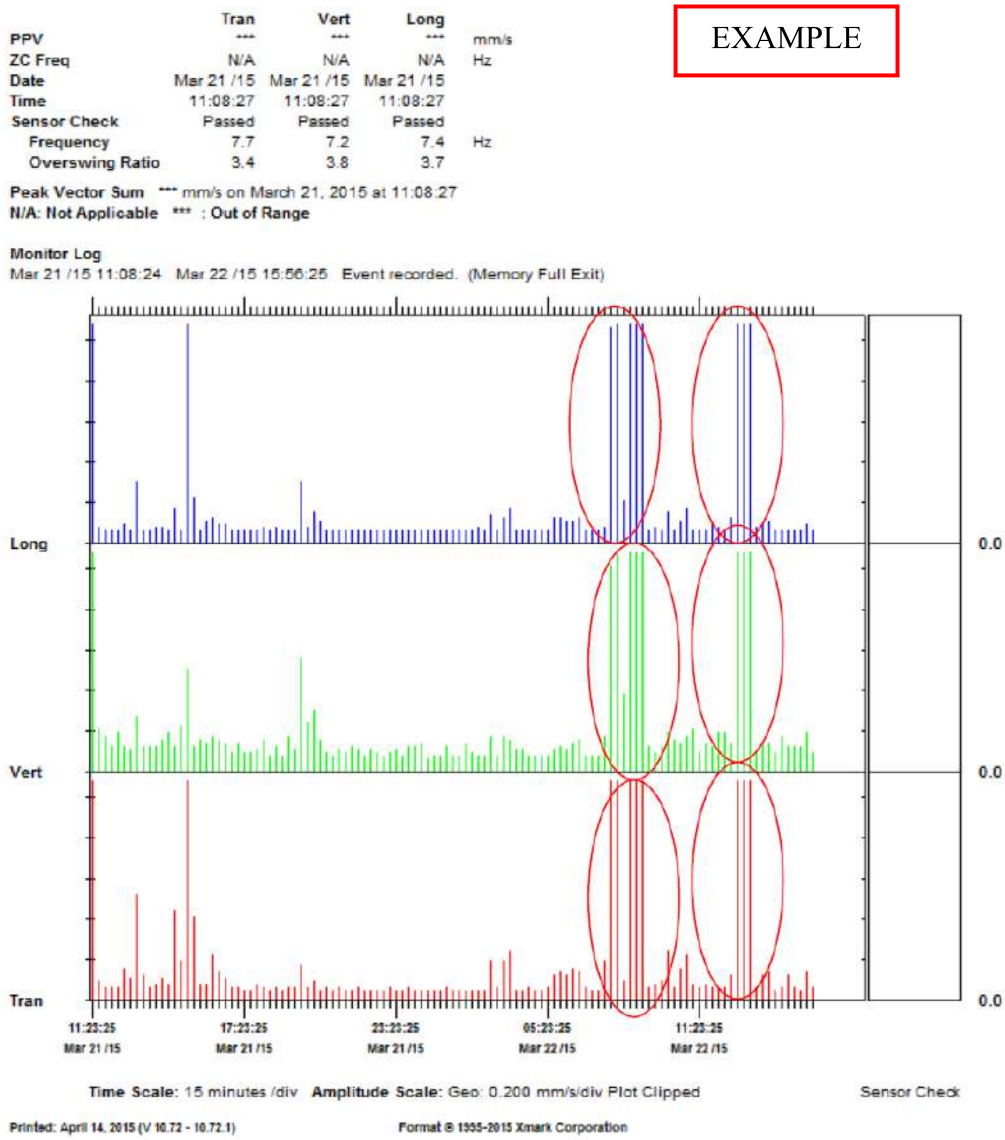


Chart B-4: Example of vibration continuous monitoring (reported in velocity ppv mm/s) at construction work site perimeter boundary.

Results presented in vibration levels vs time and plotted against ISO 2631 human response curves. Intermittent vibrations were observed



Remarks : High peaks were suspected due to workers accidently hit sensors

Chart B-5: Example of vibration continuous monitoring (reported in velocity ppv mm/s) at construction work site perimeter boundary.

Results should be checked against site activities to identify spurious results.

Chart B-6: Example of vibration (vertical direction) plotted on human response curves (ISO 2631

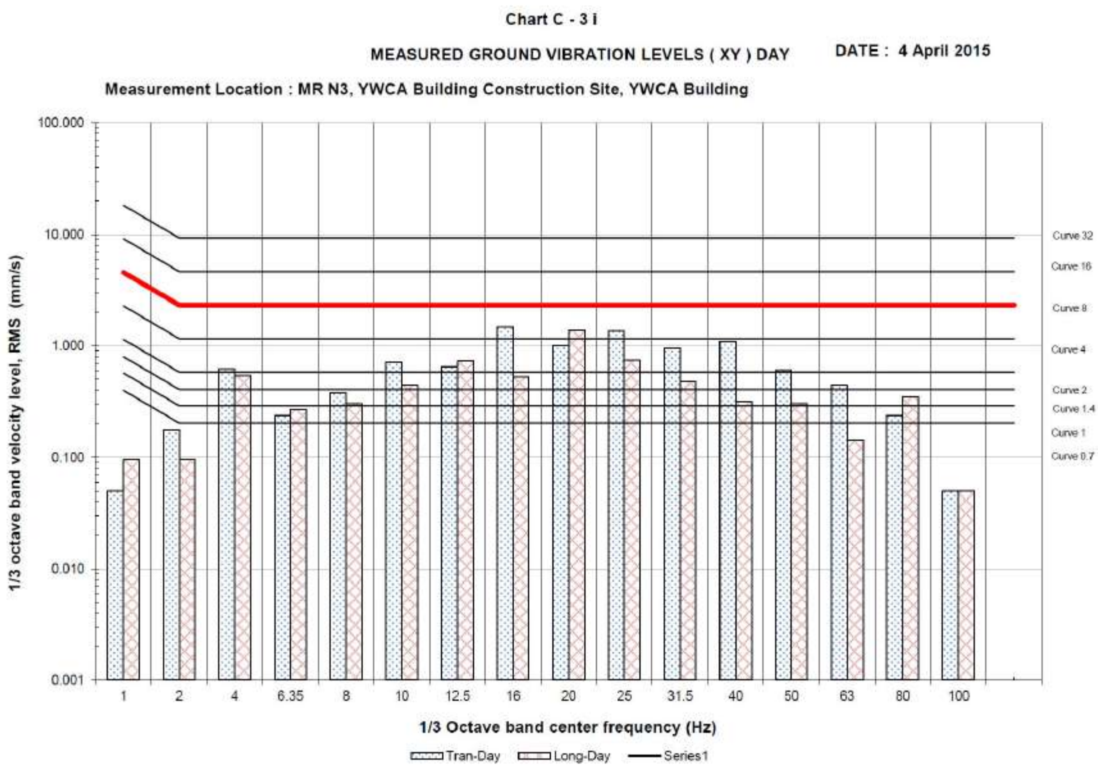


Chart B-7: Example of vibration (longitudinal and transverse directions) plotted on human response curves (ISO 2631)

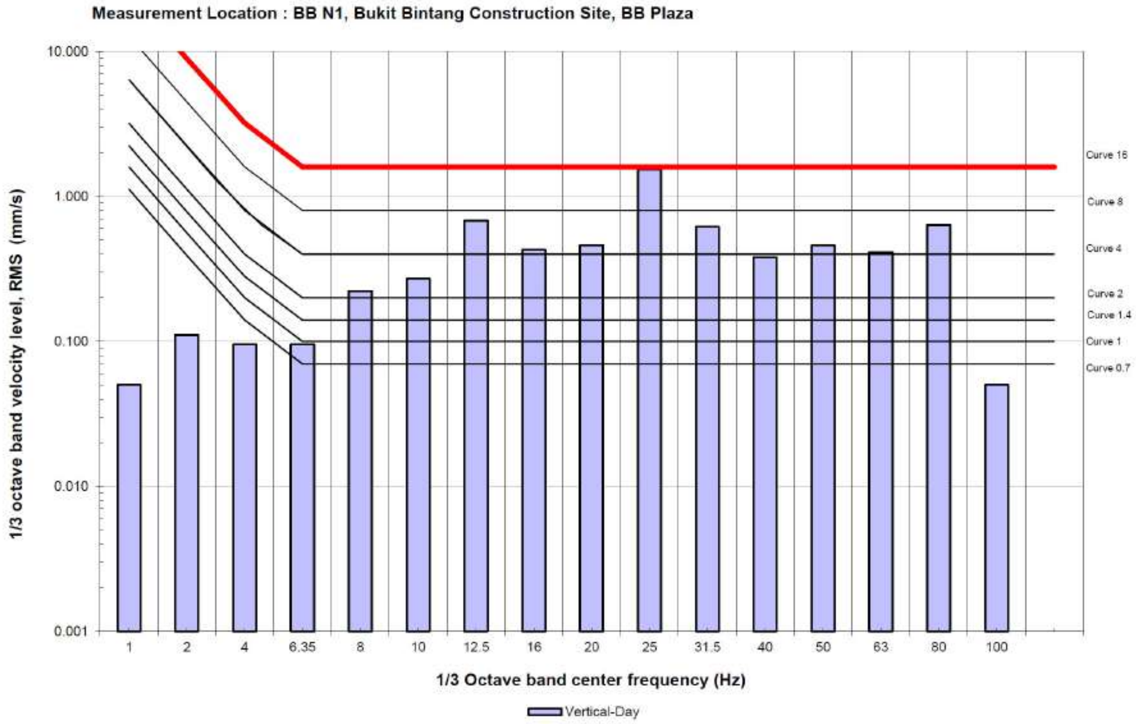


Chart B-8: Example of vibration (vertical direction) plotted on human response curves (ISO 2631

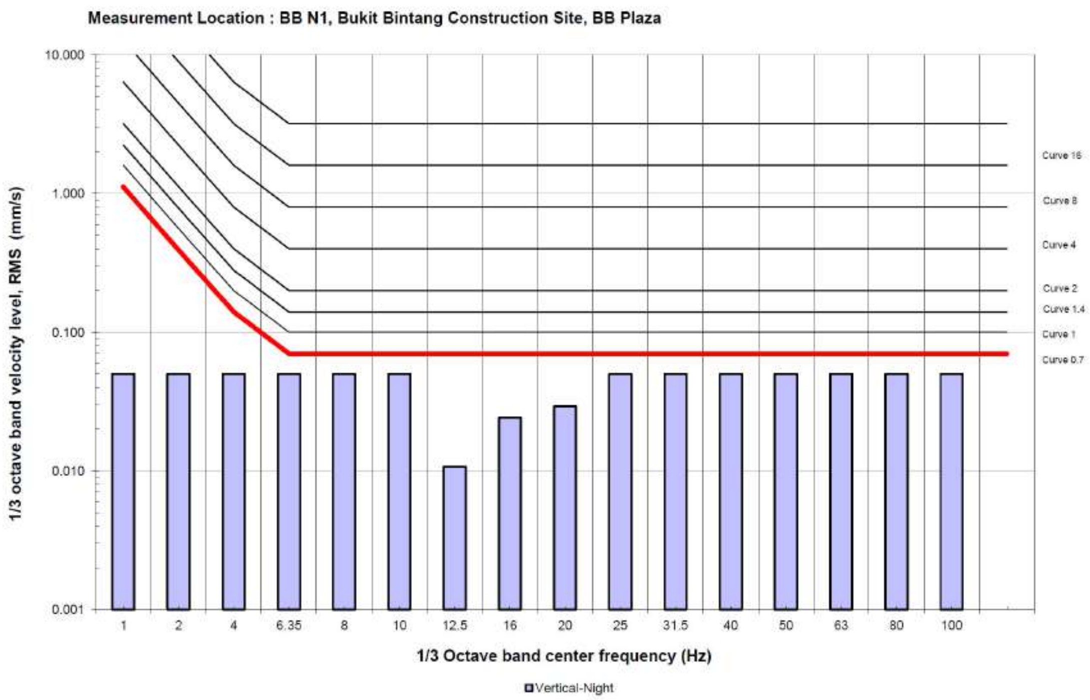


Chart B-9: Example of vibration (longitudinal and transverse directions) plotted on human response curves (ISO 2631)

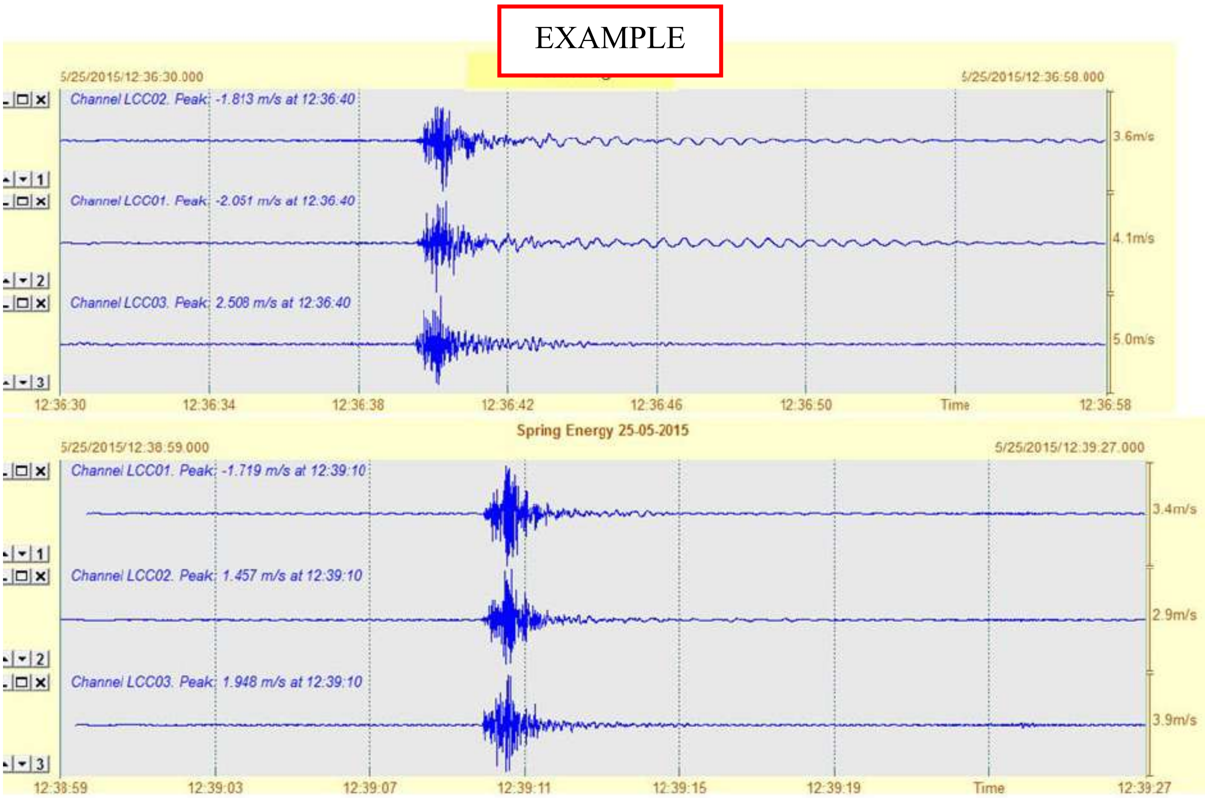


Chart B-10: Example of blasting vibration measurements (vertical, longitudinal, transverse ppv) from two different blast events

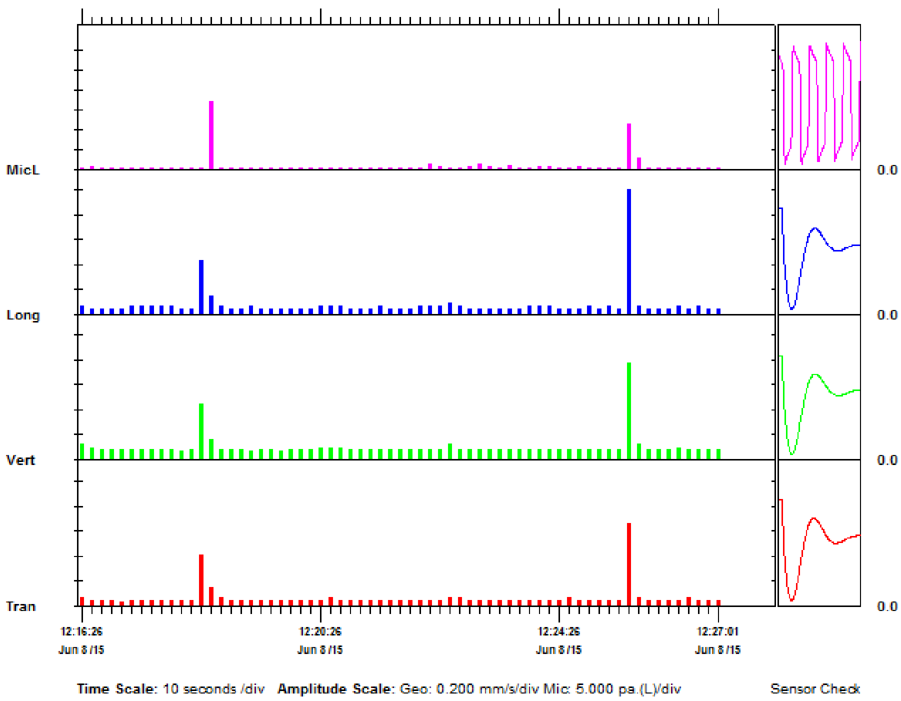


Chart B-11: Example of blasting vibration measurements (vertical, longitudinal, transverse ppv) and airblast overpressure measurements using a blast monitoring equipment

ANNEX C

PREDICTIONS OF GROUND VIBRATION

1. Vibration propagation through the ground would attenuate due geometric spreading (distance loss) and damping in the ground depending on geological conditions.

   The following equation defines the vibration level at location *b* relative to the vibration level at a known location *a*, which includes a damping constant for material loss (reference: Amick). Where the Raleigh wave propagation is dominant, γ is set to 0.5. Material damping loss ρ is dependent on the soil type.

   $$v_b = v_a \, (r_a/r_b)^{\gamma} \; e^{\rho \pi f (ra-rb)}$$ **Equation C-1**

   where

   v_a = vibration amplitude of the source at distance r_a (location *a*)
   v_b = vibration level at location *b*
   r_a = distance from source at location *a*
   r_b = distance of receptor from source at location *b*
   γ is = geometric attenuation coefficient
   ρ = material damping loss
   f = frequency of the vibration

   The amplitudes of body waves propagation in the ground decrease in direct proportion to the distance from the source , except along the surface where their amplitudes decrease in direct proportion to square of the distance to the source.

2. For environmental vibration impact assessment, the above equation for geometric spreading could be simplified into :

   $$v_b = v_a \, (r_a / r_b)^{\gamma}$$ **Equation C-2**

   The geometric attenuation coefficient depends on the wave's propagation type, and is given as follows:

Table C-1: Geometric attenuation coefficient for different waves type

Source	Wave Type	Measurement Point	γ
Point on surface	Rayleigh (R)	Surface	0.5
Point on surface	Body (P or S)	Surface	2
Point at depth surface	Body (P or S)	Surface	1
Point at depth surface	Body (P or S)	Surface	1

3. There are different types of waves in ground vibration propagation, classified as follows:

   - **Primary** or compression waves (**P-waves**) with particle motion parallel to the wave front.
   - **Secondary** or shear waves (**S-waves**) with particle motion transverse to the wave front.
   - **Rayleigh** waves (**R-waves**) with horizontal and vertical components that travel mostly near the surface.

   P waves are compression waves (primary waves) that travels in the rock in the direction of propagation. P waves travel fastest and are the first to arrive at measurement location. S waves are shear waves, and the motion is perpendicular to the direction of travel (rock vibration oscillating perpendicular to the direction of wave propagation). Rayleigh waves are surface waves travelling near the surface of rock formation. All three waves travel at different speeds, with R-waves most significant along the surface.

4. It could be observed from Table C-1 the value of γ is range from 0.5 to 2. Under practical circumstances, the value of γ depended on the manner vibration is generated and vibration propagation waves from the vibration source.

5. BS 5228-2:2009+A1:2014 gives empirical equations for the predictions of groundborne vibrations arising from mechanized construction works. The Federal Transit Authority also provide a simple equation for the predictions of vibration from construction based on a reference vibration value at a known distance. These recommendations were used in fine-tuning the geometric spreading equation based on a refence vibration level for common construction vibration sources listed in Table C-2.

Table C-2: Vibration predictions based on a reference vibration level

Constant γ	Prediction Equation C-3	Primary propagation Vibration source	Reference
0.5	$v_b = v_a(r_a/r_b)^{0.5}$	Surface	Amick
1	$v_b = v_a(r_a/r_b)$	Sub-terrain (at depth)	Amick
1.2	$v_b = v_a(r_a/r_b)^{1.2}$	Vibratory piling (start up, run down)	BS 5228-2:2009
1.3	$v_b = v_a(r_a/r_b)^{1.3}$	Percussive & vibratory piling, tunnelling	BS 5228-2:2009
1.5	$v_b = v_a(r_a/r_b)^{1.5}$	Vibratory compaction	BS 5228-2:2009
		Construction activities, piling, etc. & mechanized equipment	FTA Report 0123
1.7	$v_b = v_a(r_a/r_b)^{1.7}$	Dynamic compaction	BS 5228-2:2009

6. In practice, uncertainties in predictions are associated with the selection and use of the most appropriate value of γ; where γ = 0.5 would provide the most conservative prediction (vibrations predicted higher than actual) and γ = 2 would result in the most optimistic value (likely to be under predicted). Vibration test measurements for vibration sources of concern are therefore highly recommended for a more accurate assessment.

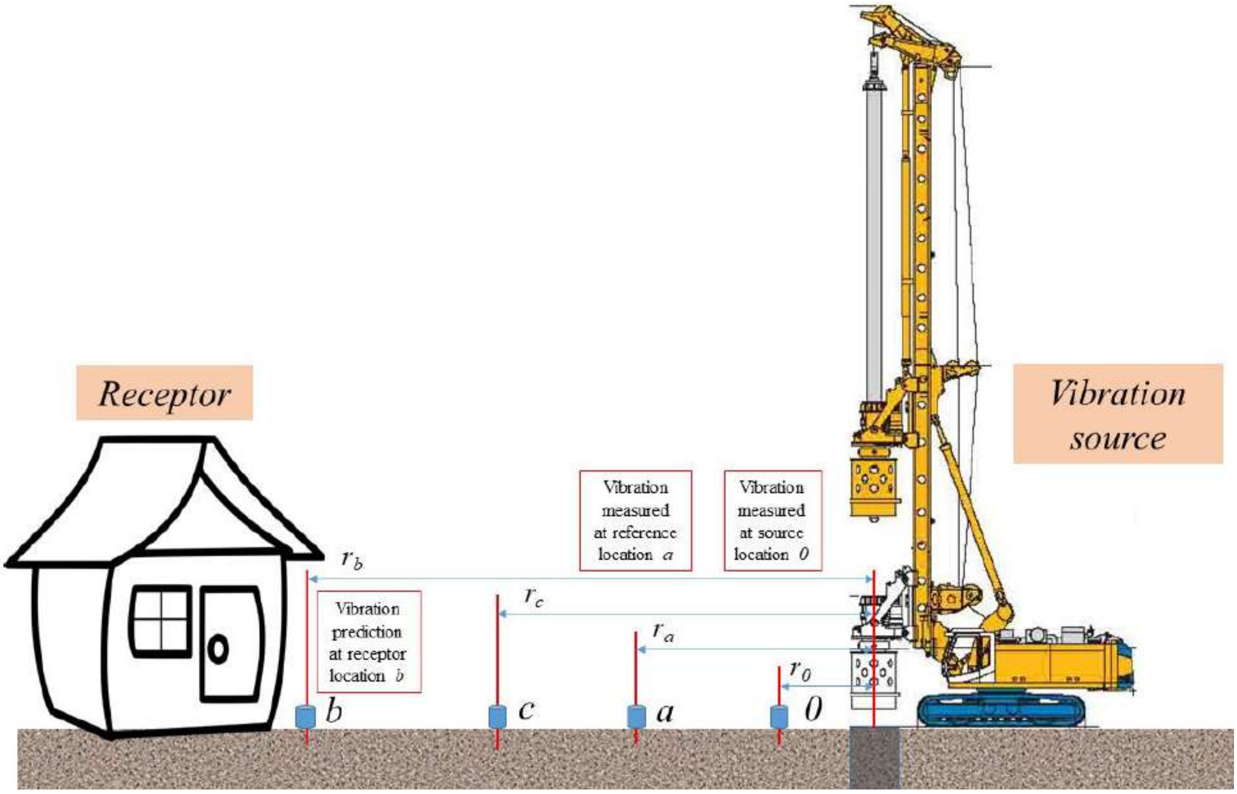


Figure C-1: Vibration test measurement set up for pile driving

7. The vibration predictions given in Equations C-1 to C-3 requires a known (measured value v_a at location *a*, or alternatively based on published data for a similar vibration source) at a known reference distance (r_a) from the source.

The preferred approach is to undertake a vibration test, preferably at the location of concern or alternatively at another location with similar geological (soil type), where the reference vibration amplitude (v_a) at a distance (r_a) can be determined. An illustration of the vibration test measurement for a vibration source (piling works) is shown, with measurements undertaken at location "*a*". The test measurement is to obtain value v_a for predictions at different locations (for different range of "*b*").

For improved accuracy, measurements should be undertaken at different distances at regular distances from the test source (preferably close to source at location "*0*" as well location "c". Results at different distances would help improve the prediction accuracies to account for variations due to material damping at different distances between source and measurement points; and in particular to establish the most the most appropriate value of constant γ. Measurements at additional locations ("c" for example) can be used to determine and validate the calculated predictions with comparison of calculated and measured v_c values.

Measurement distances at *Location a* to *Location c* should preferably be in the same range (order of magnitude) to distances requiring predictions (distance r_b) such that predictions of vibration levels would be in similar range of measured values, where feasible.

The vibration testing described above can be undertaken for all types of vibration sources (i.e., construction works, railways, highways, etc.).

Source: Institute of Noise & Vibration, UTM

Plate C-1: Vibration testing of pile driving in MRT work site for piling vibration predictions

Plate C-2: Vibration test measurements for railways ground vibration predictions

8. Plate C-1 show vibration test measurements under controlled conditions undertaken in a construction site (with vibration amplitudes correlated against piling depths, soil conditions, etc.). Plate C-2 show railways induced vibrations test measurements (with passenger and cargo trains correlated against train speeds). Testing with variations in site and source operating variables would improve predictions accuracy and establish upper and lower range in the predictions.

   In the absence of test vibration results, data from published literature can be used.

9. Examples of published vibration levels for different piling types at different distances to receptor are given in Chart C-1. (Reference: Kym Burgemeister, et.al. *"Measurement and Prediction of Construction Vibration Affecting Sensitive Laboratories",* Proceedings of Acoustics 2011, Australia). Reference vibration levels for construction equipment (at 25 ft) are also given in the Federal Transit Authority Report 0123, *Transit Noise and Vibration Impact Assessment Manual,* 2018 (Chapter 7.2 *Construction vibration assessment,* Table 7.4.

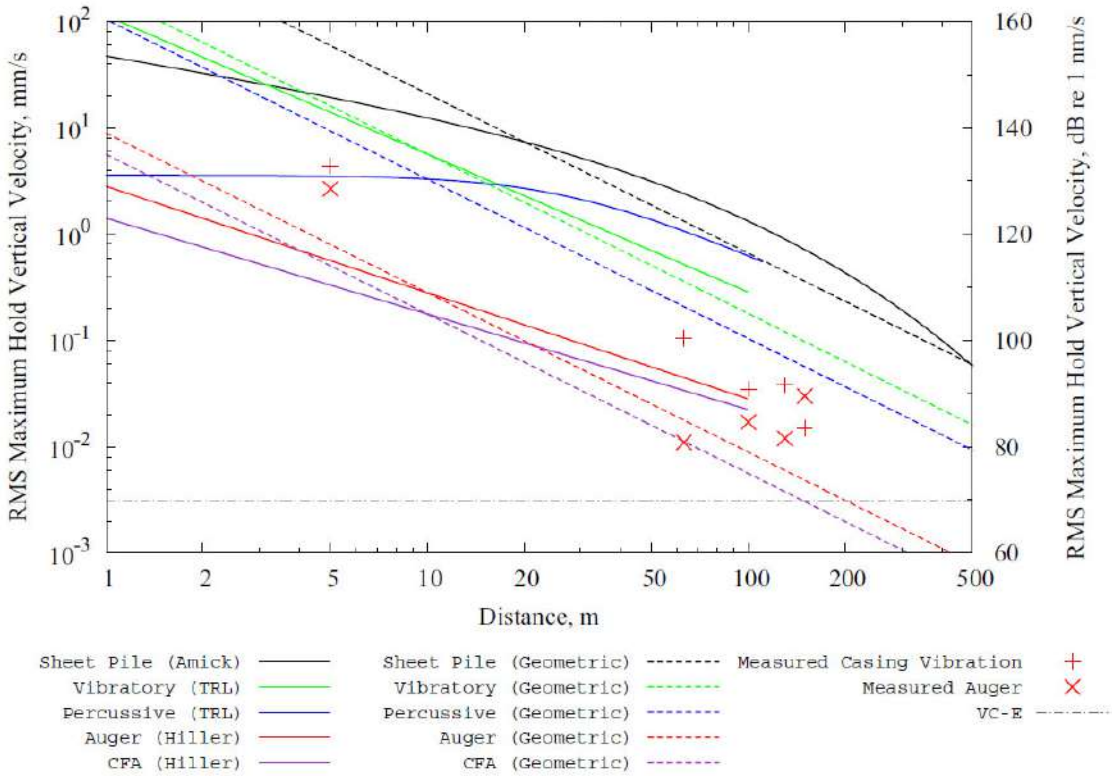


Chart C-1: Typical vibration levels for different piling types at different distances

10. In the absence of known reference vibration levels for construction works, guidance is given in BS 5228-2:2009+A1:2014 Annex E, E.1 *Prediction of vibration levels from construction activities;* where empirical equations for predictions of ground borne vibration from mechanized construction works based on assumed variables could be used. The empirical equations cover a range of mechanized construction work. Vibration test measurements are nevertheless recommended where feasible, as this would address variables and uncertainties in site and source(s) conditions.

11. Blasting induced vibrations can be predicted based on the quantity of explosives used, or alternatively from test blast vibration measurements. Vibration and airblast overpressures for a given blasting site are dependent on the quantity (weight) of explosives charge per delay per hole used (termed as the maximum instantaneous charge, kg) and the separation distance from the blast location to the receptors.

12. The most commonly used equation for vibration predictions for blasting is an empirical relationship derived by the United States Bureau of Mines (USBM) that relates ground vibration level to separation distance from a blast and the weight of explosive used. This USBM equation is as follows:

$$V = k\left[\frac{\sqrt{W}}{R}\right]^{b}$$ **Equation C-4**

Where
- V peak particle velocity (mm/s)
- k rock specific factor constant
- b constant related to rock (and site)
- W maximum instantaneous charge per delay (kg)
- R separation distance from charge (m).

The site factors *k* and *b* allow for the influence of local geological conditions and vibration attenuation in the ground as well as geometrical spreading. Values of *k* and *b* are best determined from site testing.

Table C-3: Typical Rock and Site Constants for Blasting Vibration Calculations

Description / Source	Rock Constants		Calculated Vibrations	
	k	***b***	**PPV, mm/s** (R=50m, W=1 kg)	**Difference %**
ICI Explosives Blasting Guide [a]	1896	1.6	3.63 mm/s	*Benchmark*
Australian Standards AS 2187-2: 2006 Free face average rock	1140	1.6	2.18 mm/s	-40%
Free face- hard or highly structured rock	500	1.6	0.96 mm/s	-74%
NOF Corporation Japan [b] (recommendations for Tunnels)	800	1.5	2.26 mm/s	-38%
Korean Guidelines [c]	2000	1.6	3.83 mm/s	5%
Kuala Langat Quarries [d]	1658	1.57	3.57 mm/s	-2%

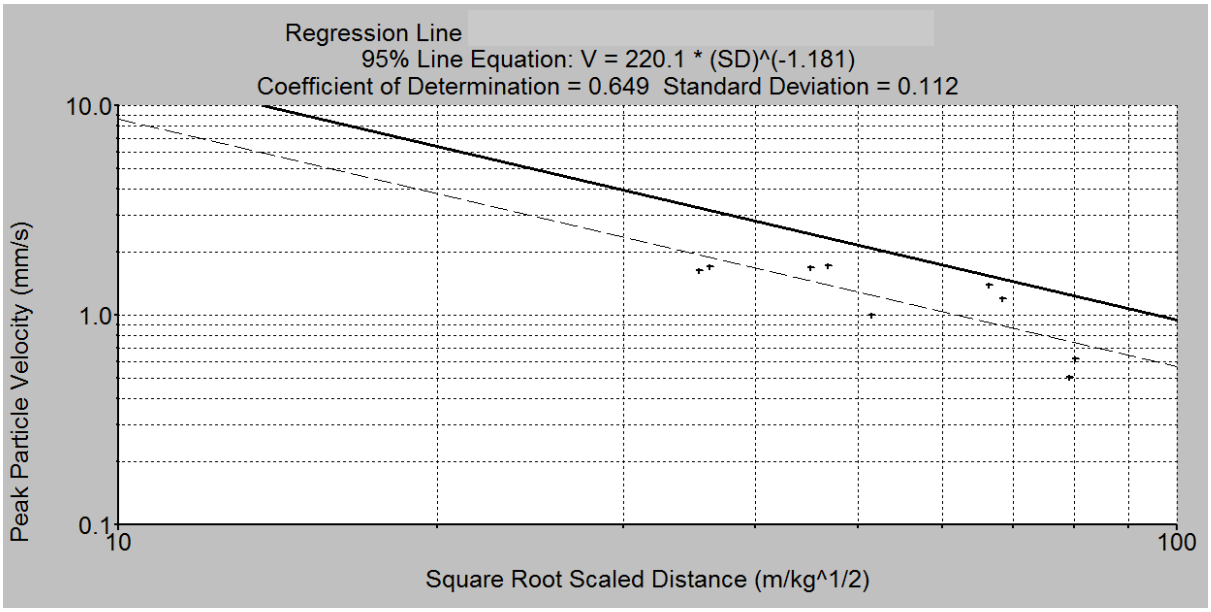
Source: (a) ICI Explosives, 1995
(b) cited by CW Lee, et al 2018, Full scale test for assessing blasting induced vibration and noise
(c) Guidelines for design and construction in open blast, Korean MCT 2006
(d) EIA, UTM Report K091203/27.10/4-EIA-SL1, 2015.

13. Typical rock specific factor and constant *k* and *b* from various references are given in Table C-3. A comparison of predicted vibration values for an example assuming 1 kg instantaneous charge per delay to a receptor 50m away is also tabulated to demonstrate the variations in predicted vibration values for based on the different *k* and *b* values assumed in the calculations.

14. The above calculation method based on separation distances and instantaneous charge weights (quantity of explosives used) allows the derivation of a site specific relationship between ground vibration level and separation distance from a blast.

$\left[\frac{R}{\sqrt{w}}\right]$ in Equation C-4 is referred to as a scaled distance *SD* (units $mkg^{-1/2}$).

15. BS 6472-2: 2008 Section 4.3 states that 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.



Source: Institute of Noise & Vibration, UTM

Chart C-2: Site specific scaled distance graph for blasting induced vibration

16. The USBM vibration prediction Equation C-4 could be expressed as a function of the scaled distance *SD* as follows:

$$v = a[SD]^b$$ **Equation C-5**

where *a* peak particle velocity intercept at unity scaled distance
b slope of the regression line.

The values of *a* and *b* are derived for a specific site based on vibration measurements at several distances from one or several blasting; and from least squares regression analysis of the logarithmic plot of peak particle velocity against scaled distance to obtain a mathematic best fit straight line.

17. A site specific scaled distance graph would thus be obtained. This graph, i.e., governing equation for the peak particle velocity scaled distance relationship, can then be used to determine the likely vibration magnitudes at any required distance for a given explosives instantaneous charge.

Vibration limits should be expressed as a statistical average to take into account of data scatter. The scaled distance graph could be determined for 90% (or 95%) confidence level or 50% confidence level. Conservative predictions dictate the use of the 90% (or 95%) confidence level graph. A typical example is given in Chart C-2.

18. From the scaled distance equation which is site specific, blasting induced vibration could be predicted for a range of distances and n particular to receptors of concern. The predicted vibration levels could be used to generate a vibration map showing predicted vibration levels from locations of the blasting location (blasting rock face). An example of the vibration map is shown in Section 11: Vibration Mapping, Plate 11-1.

ANNEX D

PROCEDURES FOR ASSESSMENT OF VIBRATION IN THE ENVIRONMENT

1. A quantitative assessment of noise involves measuring (or predicting) vibrations levels and comparing the amplitudes against recommended acceptance levels. Acceptance levels depends on the criterion of assessment.

2. Vibration acceptance criterion for vibration in the environment are as follows:
   i. Potential structural damage.
   ii. Effects on human (human response ranging from motion sickness to annoyance).
   iii. Effects on vibration sensitive equipment.

   In addition to the above criterion, there are also mechanical machines limits outside the scope of environmental vibrations, not considered in this Guidelines.

3. The vibration acceptance limits recommended in this Guidelines and most international standards and guidelines are based on vibration velocity (mm/s).

4. Schedules given in this Guidelines shall be used for impact assessment based on vibration velocity relating to human response and building occupancy, as summarized in the table below.

Table D-1: Vibration Limits Schedules to be used for Assessment.

Types	Continuous vibrations	Intermittent vibrations	Impulsive vibration
Assessment for Human response	Second Schedule	Third Schedule, Fourth Schedule	Seventh Schedule
Cosmetic damage	Sixth Schedule	Fifth Schedule	Seventh Schedule
Generic general assessment	Fist Schedule, Ninth Schedule	Fist Schedule, Ninth Schedule	Fist Schedule, Ninth Schedule
Examples	Continuous construction activities (tunnel boring, slurry treatment plant, etc.), ambient road traffic, machinery operations in buildings.	Impact pile driving, intermittent construction (e.g., hacking, jack hammers, mechanized rock breaking or demolition), power press, railway trains, heavy vehicles passing by.	Blasting using explosives, dropping of heavy loads.

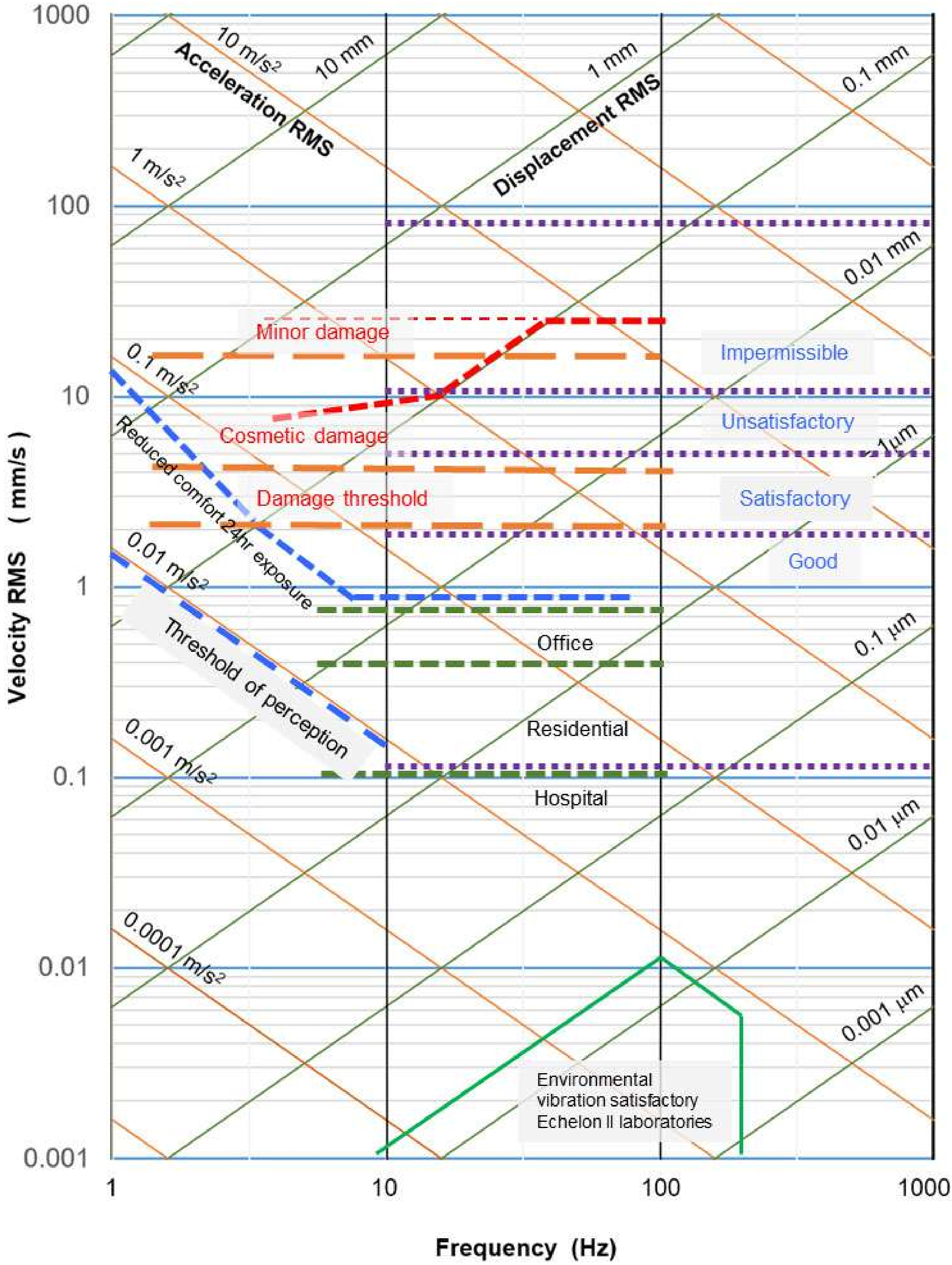


Chart D-1: Acceptance criteria for continuous vibration

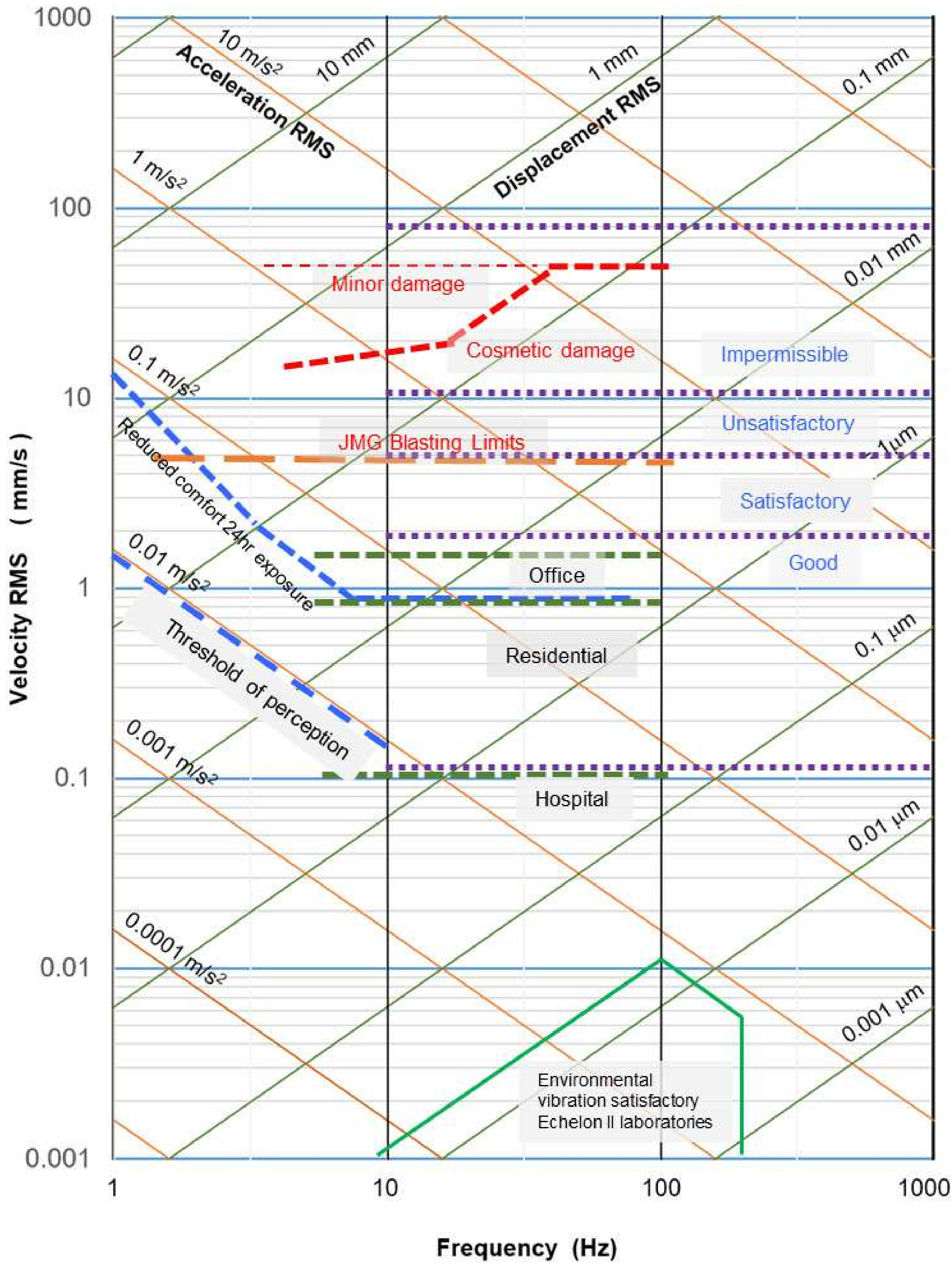


Chart D-2: Acceptance criteria for intermittent vibration

5. Vibration can be measured in acceleration (m/s^2), velocity (mm/s) and displacement (μm). Measurement units are interchangeable and be converted based on the respective vibration frequency. (Refer to Annex A for information).

6. A comparison of the acceptance limits for different assessment criterion based on measurements or predictions for vibration acceleration, velocity or displacement is given in Chart D-1 for continuous vibrations and Chart D-2 for intermittent vibrations.

7. Vibration assessment is in principle a numerical evaluation of the measured or predicted vibration levels against the appropriate Schedules prescribed in this Guideline.

8. Measurements could also be plotted against the vibration Standards based on the amplitudes and dominant frequency plotted in the frequency domain chart (amplitude vs frequency).

   An example of the graphical plot for assessment against DIN 4150 limits (auto-generated by the vibration analyser) is shown in Chart D-3. Similar plots of measured vibration (with amplitudes and frequency information) can also be plotted against BS-7385-2:1993 limits (in accordance with the 5th and 6th Schedules). Examples are given in Annex B (Plate B-22 and Plate B-23).

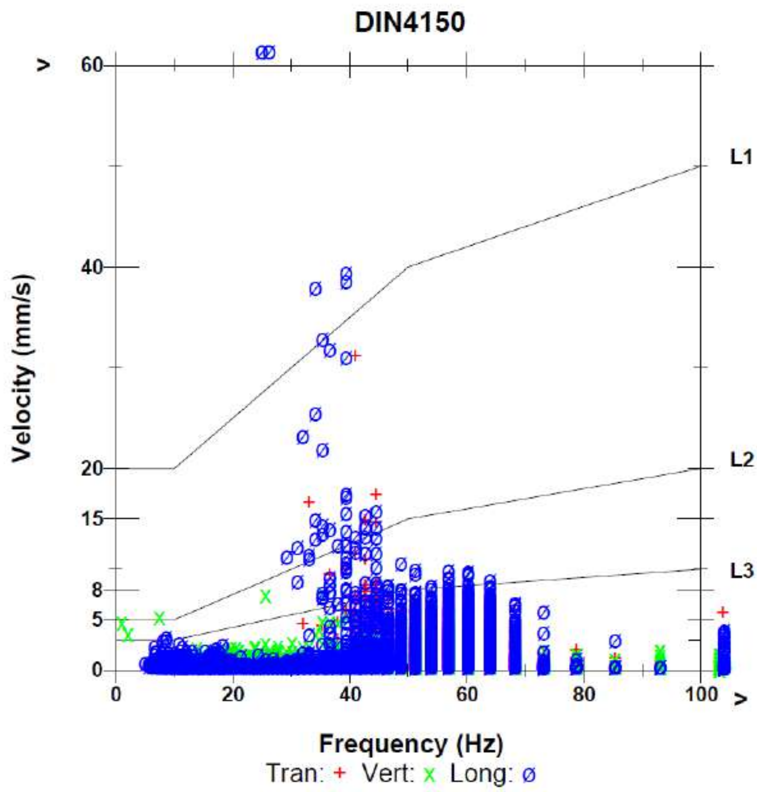


Chart D-3: Example of vibration measured from construction activities assessed against potential damage

9. In addition to assessment of vibration levels based on numerical limits corresponding to likely human response and damage criterion given in the Second to Eighth Schedules, it is possible to assess vibrations based on human perception and the likely reaction to the perceived vibration.

   The Nineth Schedule of this Guideline can be used to determine likely human perception to vibrations. This table is reproduced from BS 5228-2:2009+A1:2014, Annex B, Table B.1 *Guidance on effects on vibration levels*.

10. The Nineth Schedule of this Guideline can be used to give an initial indication of potential effects of vibrations.

11. Qualitive descriptors used in general assessment of vibration severity are also indicated in Chart D-1 and D-2 based on descriptors of *good*, *satisfactory, unsatisfactory,* and *impermissible*. These are usually used for machinery induced vibrations.

12. For the purpose of quantifying residual impact in Environmental Impact Assessment, generalised descriptors corresponding to human perception (as indicated in the Nineth Schedule) are given in Table D-2.

Table D-2: Human perception of vibration and likely environmental impact

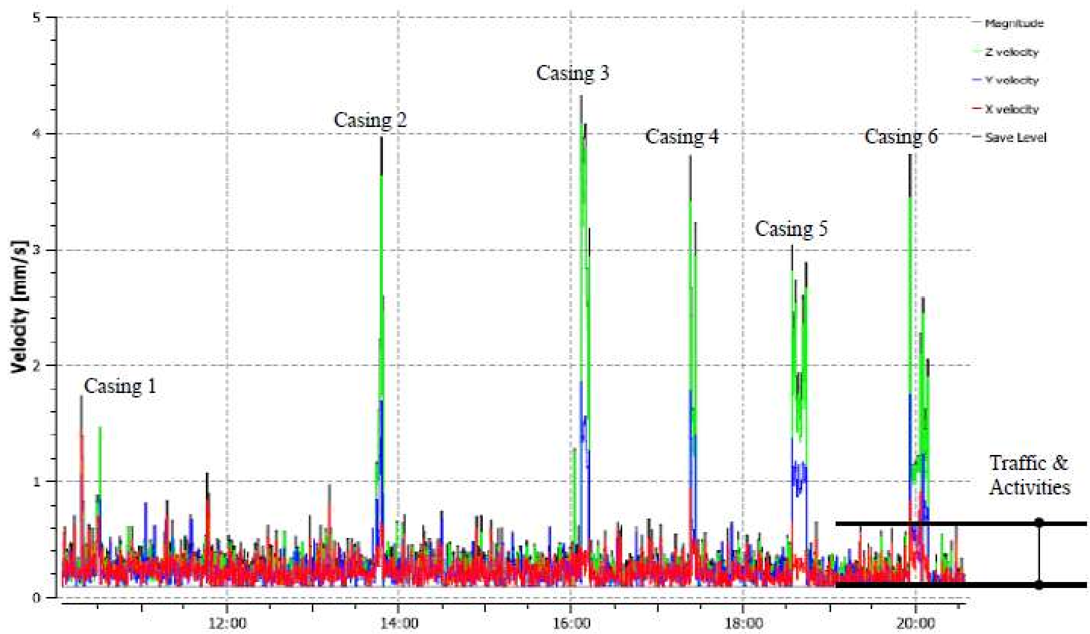
Approximate vibration level (Peak Particle Velocity)	Degree of perception	Environmental Impact
0.14 mm/s	Threshold of perception	None
0.3 mm/s	Barely noticeable	Little
1.0 mm/s	Noticeable	Medium
2.2 mm/s	Easily noticeable	Strong
6 mm/s	Strongly noticeable	Very strong

13. Vibrations that occur intermittently can also be assessed using the Vibration Dose Value (VDV) in accordance with the Fourth Schedule.

14. Examples

i. Chart D-4 below shows a vibration time history plot (ppv amplitude vs time) measured in vertical, horizontal and transverse (x, y, z) directions monitored continuously over the piling activities period (10 hours) at the highway leading to Penang Bridge.

The vibration plots showed high vibration events from the piling works, amongst the prevailing busy highway bridge road traffic. Undertake an assessment of the road traffic and piling vibrations based on limits recommended in this DOE Vibration Guidelines.



Source: Institute of Noise & Vibration, UTM

Chart D-4: Vibration measured from piling works in a highway bridge construction

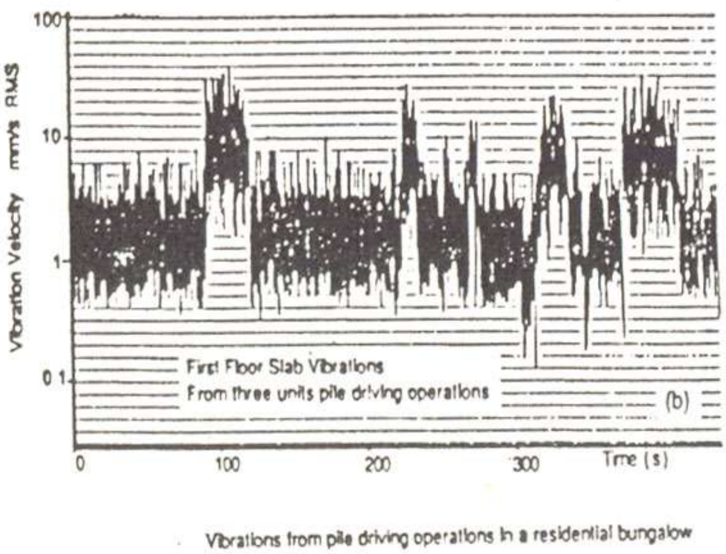
As seen from the above vibration magnitude vs time plot, the steady state road traffic vibrations were typically 0.6 mm/s ppv. Piling vibrations ranged from 1.8 mm/s ppv (Casing1) up to 4.4 mm/s ppv (Casing 3).

Steady state road traffic vibration assessed on human response using the Second Schedule were within recommended limits of R= 8 (0.8 mm/s) day time but exceed R= 4 (0.4 mm/s) for commercial receptors; and also exceed day and night limits for residential receptors. The vibrations assessed against cosmetic damage for continuous vibrations using the Third Schedule were within recommended limits of 7.5 mm/s for residential and light commercial buildings.

The intermittent vibrations from piling works assessed using the Third Schedule exceed recommended limits for human response of R = 16 for residential and commercial receptors. The piling vibrations were with cosmetic damage limits assessed against the Sixth Schedule.

ii. The photograph in Plate D-1 below shows piling vibrations in progress from a construction site adjacent residential house (bungalows). The vibration velocity plotted against time for the piling impacts are shown in Chart D-1. Undertake an impact assessment for human response and potential structural damage.

Plate D-1: Drop hammer impact piling works at condominium project site next to existing residential houses

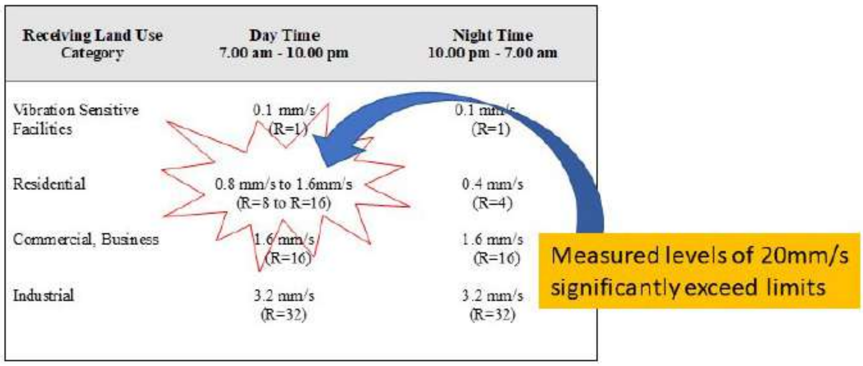


Source: Institute of Noise & Vibration, UTM

Chart D-5: Vibration measured from drop hammer impact piling works at condominium project site next to existing residential houses

THIRD SCHEDULE

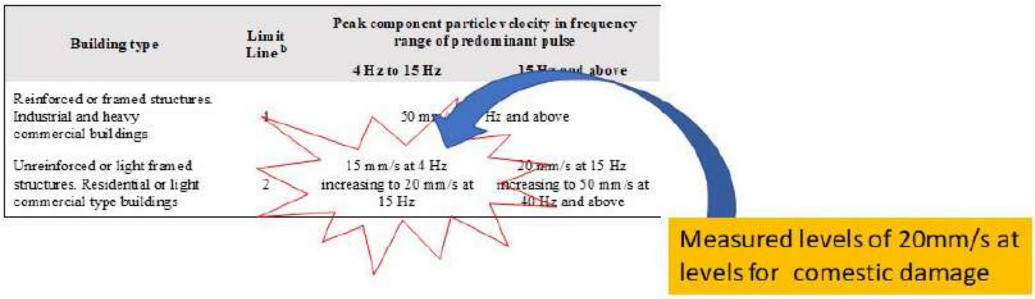
RECOMMENDED VIBRATION LIMITS FOR HUMAN RESPONSE AND ANNOYANCE FROM INTERMITTENT VIBRATIONS



Receiving Land Use Category	Day Time 7.00 am - 10.00 pm	Night Time 10.00 pm - 7.00 am
Vibration Sensitive Facilities	0.1 mm/s (R=1)	0.1 mm/s (R=1)
Residential	0.8 mm/s to 1.6mm/s (R=8 to R=16)	0.4 mm/s (R=4)
Commercial, Business	1.6 mm/s (R=16)	1.6 mm/s (R=16)
Industrial	3.2 mm/s (R=32)	3.2 mm/s (R=32)

SIXTH SCHEDULE

GUIDE VALUES FOR INTERMITTENT VIBRATION RELATING TO COMESTIC DAMAGE



Building type	Limit Line [b]	Peak component particle velocity in frequency range of predominant pulse	
		4 Hz to 15 Hz	15 Hz and above
Reinforced or framed structures. Industrial and heavy commercial buildings	1	50 mm/s at 4 Hz and above	
Unreinforced or light framed structures. Residential or light commercial type buildings	2	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

The charts recording of piling vibrations (Chart D-5) showed intermittent peak vibration events corresponding to the pile driving (from 3 piling machines). The peak vibration levels typically ranged from 5mm/s to more than 20 mm/s, repeated one to 2 minutes (60 to 120 seconds).

Using the Third Schedule for assessment against human response, the piling vibrations in the order of 20mm/s were significantly higher than the recommend daytime limits of 1.6mm/s. The Nineth Schedule (based on BS 5228-2:2009) states that the vibration is likely to be intolerable for *any more than a very brief exposure*.

At these vibration levels, structure damage was a real concern. Assessed against the Sixth Schedule (based on BS 7385-2:1993), cosmetic damage was expected in residential buildings, which indeed did occur to the affected house.

The vibrations were deemed highly intolerable by the building occupants (which led to the measurements being undertaken and typical results shown here). There was structural damage (minor damage) with cracks at walls termination against beam, aggravated with settlement cracks.

There was a subsequent civil litigation filed by the affected receptor for damages (and compensation paid) against the party responsible for the piling works and adjacent development.

iii. Chart D-6 below shows a vibration spectrum measured on the floor slab in an electronic factory with vibration sensitive facilities. The 1/3 octave centre band frequencies spectral components from 6.3 Hz to 80 Hz are plotted. What vibration rating curve is the measured vibration and whether it complies with the recommended design criteria of VC-C (for example an imaging equipment required in an MRI facility? Is this vibration plot was measured in an operating theatre, would this be acceptable (assuming a generic criteria of R=1)?

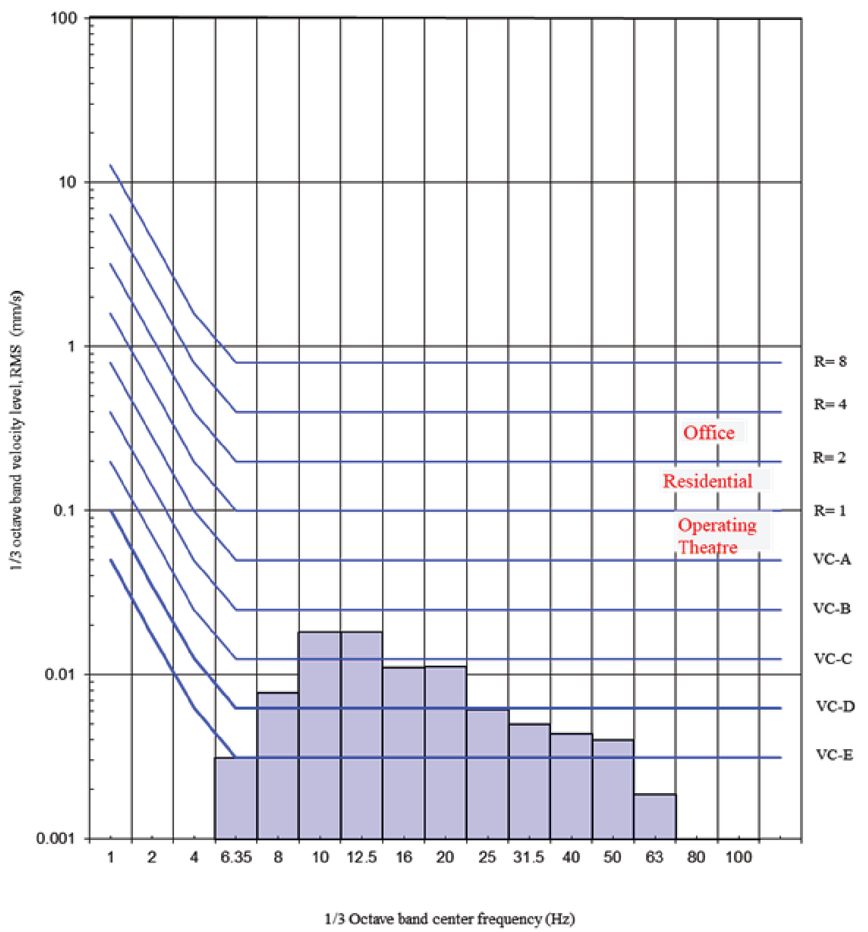


Chart D-6: Example of measured vibration spectrum and assessment against vibration rating curves

The measured vibration spectral levels showed vibration components below the VC-B curve but above the VC-C curve.

The measured vibration is therefore *below the VC-B rating curve*, but *exceeds the recommended design criteria of VC-C*. It exceeds the recommended criteria required in an MRI imaging facility. The vibration is well within an acceptance limit required in an operating theatre assuming an acceptance criterion of R=1 rating curve.

iv. Piling vibrations were measured at a project site with typical maximum levels during pile driving of 22.5 mm/s, measured at a distance 5m from pile location.

Determine the likely vibration levels that may be perceived at receptors at 25m, 50m and 100m away from the piling site based on the following assumptions:
(a) Primary waves propagation with predominant ground surface propagation
(b) Vibration propagation for piling based on empirical relationships (BS 5228).

Using Equation C-2, Annex C for predictions of ground vibration

$$v_b = v_a\,(r_a / r_b)^{\gamma}$$

Reference vibration v_a = 22.5 mm/s and r_a = 5 m

a. Primary waves propagation with predominant ground surface propagation
Value of γ = 0.5

Distance r_b = 25m
Vibration at 25m, $v_b = 22.5 \times (5/25)^{0.5} = 10.1$ mm/s

Distance r_b = 50m
Vibration at 50m, $v_b = 22.5 \times (5/50)^{0.5} = 7.1$ mm/s

Distance r_b = 100m
Vibration at 100m, $v_b = 22.5 \times (5/100)^{0.5} = 5.0$ mm/s

b. Rayleigh waves propagation with horizontal and vertical components near the surface
Value of γ = 1.3

Distance r_b = 25m
Vibration at 25m, $v_b = 22.5 \times (5/25)^{1.3} = 2.8$ mm/s

Distance r_b = 50m
Vibration at 50m, $v_b = 22.5 \times (5/50)^{1.3} = 1.1$ mm/s

Distance r_b = 100m
Vibration at 100m, $v_b = 22.5 \times (5/100)^{1.3} = 0.5$ mm/s

The above predictions showed different vibration levels due to differences in the assumed value of γ used related to variations in the manner of ground vibration propagation that are often site dependent. Test piles measurements are recommended. Uncertainties in predictions also dictate that monitoring during actual piling works should be undertaken. Results predicted in part (i) with **γ = 0.5** are worst case scenario, and results predicted in part (ii) with **γ = 1.3** are the more probable scenario.

Vibrations would be *noticeable with medium impact* for receptors 50m away, based on a general assessment using Table D-2 (BS 5228-2:2009+A1:2014) for results predicted with **γ = 1.3**.

v. Tunneling works are required for the construction of an underground portal in an interstate highway project. What is the predicted blasting induced vibration for receptors at 75m and 250m if the conventional drill and blast tunneling method is to be used during construction?

Blasting induced vibrations are dependent on the quantity of explosives used (maximum instantaneous charge i.e., maximum amount of explosive in kg on any one specific delay detonator in any one blast hole, *W*), distance from blasting (*R*) and site factors (geological formation and ground attenuation constants *k* and *b*).

Refer to Equation C-4 and Table C-3, Annex C, blasting vibrations could be predicted based on quantity of explosives (*W*) used.

$$V = k\left[\frac{\sqrt{W}}{R}\right]^b$$

In the absence of site testing, values of *k* and *b* were assumed based on ICI Explosives Blasting Guide as follows: $k = 1896$ and $b = 1.6$

Consider two (or more) likely values of explosives: 2 kg and 5 kg maximum instantaneous charge per delay as follows:

a. W = 2 kg maximum instantaneous charge per delay

For R = 75 m,

$$v = 1896\left[\frac{\sqrt{W}}{R}\right]^{1.6} = 1896\left[\frac{\sqrt{2}}{75}\right]^{1.6} = 3.3\ mm/s$$

For R = 250 m

$$v = 1896\left[\frac{\sqrt{W}}{R}\right]^{1.6} = 1896\left[\frac{\sqrt{2}}{250}\right]^{1.6} = 0.5\ mm/s$$

b. W = 5 kg maximum instantaneous charge per delay

For R = 75 m,

$$v = 1896\left[\frac{\sqrt{W}}{R}\right]^{1.6} = 1896\left[\frac{\sqrt{5}}{75}\right]^{1.6} = 6.8\ mm/s$$

For R = 250 m,

$$v = 1896\left[\frac{\sqrt{W}}{R}\right]^{1.6} = 1896\left[\frac{\sqrt{5}}{250}\right]^{1.6} = 1.0\ mm/s$$

Results are tabulated as follows:

Max. Instantaneous Charge, kg	**Ground Vibration from Blasting**	
	75 m	**250 m**
2kg	3.3 mm/s	0.5 mm/s
5kg	6.8 mm/s	1.0 mm/s

The above predicted vibration levels should be assessed for human response and potential structure damage using the Seventh and Eighth Schedules respectively. Ground vibration contours from the blasting site, similar to Section 11.0, Plate 11-1, should be plotted for a more comprehensive assessment.

vi. Examples of vibration dose value (VDV) used in annoyance assessment based on vibration levels and duration of exposure are given below.

(a) Overall vibration acceleration RMS averaging 0.0383 m/s^2 was measured in an apartment building with extended intermittent vibration operating over a total duration of 4 hours per day.

What is the vibration dose, and probability of adverse comments?

Vibration dose can be estimated (*eVDV*) as follows, refer Equation 5-2, Section 5.

$$eVDV = k \times a_{rms} \times t^{0.25}$$

where k = 1.4 (nominal value for crest factors below 6).
a_{rms} = weighted rms acceleration (m/s^2)
t = total cumulative time (secs) of vibration events or duration.

In this example, a_{rms} = 0.0383 m/s^2
t = 4 x 2600 seconds

$$eVDV = 1.4 \times 0.0383 \times (4 \times 3600)^{0.25}$$
$$= 0.59\ m{\cdot}s^{-1.75}$$

Referring to the Fourth Schedule for residential buildings, VDV of 0.5 would likely result in *adverse comment possible*.

(b) In the above example, measurements were instead undertaken in vibration velocity, where the velocity was 0.76 mm/s. Duration of vibration is 4 hours/day.

This vibration velocity levels are consistent with a dominant vibration frequency response of 8 Hz: noting that $V = A / (2 \pi f) = [0.0383 / (2 \pi 8)] \times 1000$ = 0.7619 mm/s.5,

Estimate the vibration dose based on vibration velocity approximation.

Using Equation 5-4, Section 5,

$$eVDV = 0.07 \times v_{rms} \times t^{0.25}$$
$$= 0.07 (0.76) \times (4 \times 3600)^{0.25}$$
$$= 0.58\ m{\cdot}s^{-1.75}$$

(c) Vibration velocity measurements from an urban transit train line were measured at two residential receptor's locations: receptors A in close proximity to the rail tracks, and receptors B further away (approximate 150m away). Typical pass-by (peak events) vibration velocity rms levels at receptors A were 1.2 mm/s rms, and at receptors B were 0.4 mm/s. Trains pass by events averaged 8 seconds per train pass-by, with 24 trains per hour operating 18 hours per day.

What is the vibration dose, and probability of adverse comments at the two receptor's locations?

Refer Equation 5-4, Section 5,

$$eVDV = 0.07 \text{ x } v_{rms} \text{ x } t^{0.25}$$

Total cumulative time of vibration events

$$t = 8 \text{ (sec per event) x 24 (trains) x 18 (hours per day)}$$
$$= 3456 \text{ seconds}$$

At receptors *A*, for v_{rms} = 1.2 mm/s

$$eVDV = 0.07\ (1.2) \text{ x } (3456)^{0.25}$$
$$= 0.64 \text{ m·s}^{-1.75}$$

At receptors *B*, for v_{rms} = 0.4 mm/s

$$eVDV = 0.07\ (0.4) \text{ x } (3456)^{0.25}$$
$$= 0.21 \text{ m·s}^{-1.75}$$

Referring to the Fourth Schedule, receptors *A* adjacent the railway tracks with a vibration dose value (VDV) of 0.64 m·s$^{-1.75}$ is anticipated to have *adverse comment possible.*

Receptors *B* further away with a vibration dose value (VDV) of 0.21 m·s$^{-1.75}$ is anticipated to have *low probability of adverse comment.*

FOURTH SCHEDULE

VIBRATION DOSE VALUE RANGES WHICH MIGHT RESULT IN VARIOUS PROBABLITIES OF ADVERSE COMMENT WITHIN BUILDINGS

Receptors	Time period	Low probability of adverse comment VDV_b m·s$^{-1.75}$	Adverse comment possible VDV_b m·s$^{-1.75}$	Adverse comment probable VDV_b m·s$^{-1.75}$
Residential buildings	16 h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
	8 h night	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8
Office buildings	16 h day	0.4 to 0.8	0.8 to 1.6	1.6 to 3.2
	8 h night	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Workshop buildings	16 h day	0.8 to 1.6	1.6 to 3.2	3.2 to 6.4
	8 h night	0.4 to 0.8	0.8 to 1.6	1.6 to 3.2

ANNEX E

MANAGEMENT AND MITIGATION OF VIBRATION IN THE ENVIRONMENT

Mitigation and management measures that shall be used to control vibration in the environment are described in this section.

This section presents management aspects, mitigation measures and examples of typical measures for common vibration sources. In addition to mitigation measures, community engagement shall also be used in resolving complaints and addressing expectations of affected receptors.

It is to be noted that any mitigation and management shall be determined on a site specific basis which should be practical and reasonable.

E-1 Administrative Control

Administrative procedures relate to general measures which may be used to avoid or reduce vibration and noise impacts.

Significant measures involve the following:

- Selection of quieter equipment and work process.
- Compliance to permitted working hours.
- Scheduling of work tasks to avoid quiet periods of the day.

Other general measures include:

- Provide an induction to site personnel and contractors in addressing the requirements of the management and mitigation plan and their responsibilities with regard to noise and vibration to ensure work hours and appropriate mitigation measures are utilised.
- Provide ongoing education of supervisors, operators and sub-contractors on the need to minimise noise and vibration through toolbox meetings and on-site training.
- Include contractual requirements that require minimisation of noise and vibration in subcontractor agreements.
- Provide a procedure for handling noise and vibration complaints that includes recording, reporting and acting on complaints.
- Organise work to be undertaken during the normal working hours where reasonable and practical and safe to do so.
- Include an outside normal working hours procedure to minimise the impact of any significant noise and vibration works outside the normal hours.
- Avoid shouting and minimise talking loudly and slamming vehicle doors.
- Avoid the use of horns and alarms within the construction area, except in the case of emergency or a requirement for safety.

a. Tasks Management

High noise and vibration events or work process need to be identified and planned prior to the work activities so that the emission levels could be minimized.

i. Identify all work tasks with high noise and vibration events and process and/or noisy and high vibration impact equipment.
ii. Identify alternative work process or equipment where feasible.
iii. Scheduling the use of vibration causing equipment (e.g., jack hammers) at the least sensitive time of day.
iv. Identify and implement noise & vibration mitigation measures.
v. Plan work tasks for demolition, earth moving and ground impacting operations so as not to occur in the same time period – preferably to be done during the least disruptive time of the day.
vi. Avoid night time activities whenever possible. The EIA Approval Conditions prohibit construction works after 7pm as well as on Sundays and public holidays, unless stated otherwise.
vii. Inform stakeholder about the nature of the construction work stages and high noise and vibration generating activities; as well as mitigation measures to be undertaken to minimize emissions and disturbance.
viii. Inform stakeholder of special events or work activities that may result in noise & vibration disturbance.

b. Specification and Substitution

Where a construction site is within a sensitive area, the plant and activities to be employed on that site shall be reviewed to ensure that quietest available, alternatives to high noise and impactive piling; and mitigation measures to be undertaken in accordance with best practicable means.

The Contractor shall specify vibration emissions limits for equipment and/or activities, and to check for compliance to maximum permissible levels from vibration monitoring. For an existing operational site, where reasonably practicable, high vibration equipment or activities shall be substituted with low vibration alternatives.

c. Use and placement of equipment

- Plant and equipment shall always be used in accordance with manufacturers' instructions.
- Care shall be taken to site equipment away from sensitive areas. Where possible, loading and unloading should also be carried out away from such areas. Special care is necessary when work has to be carried out at night, but it might be possible to carry out quiet activities during that time.
- Materials should be lowered whenever practicable and should not be dropped. This includes casing handling in piling works. Surfaces of materials that are being moved should be covered by resilient material.
- When a site is in a residential environment, lorries should not arrive at or depart from the site at a time inconvenient to residents.

d. Maintenance

Regular and effective maintenance will help reduce vibration and noise generated from plant and machinery. Increase in equipment noise are often indicative of impending mechanical failure. Noise caused by vibrating machinery having rotating parts can be reduced by attention to proper balancing. Frictional noise from the cutting action of tools can be reduced if the tools are kept sharp. Noises caused by friction in conveyor rollers, drive systems and machines can be reduced by proper lubrication.

E-2 Engineering Control

Vibration mitigation by means of engineering control involves one or combination of measures to address the vibration generation and propagation at source, transmission path and receptors. Basic elements are illustrated in Figure E-1.

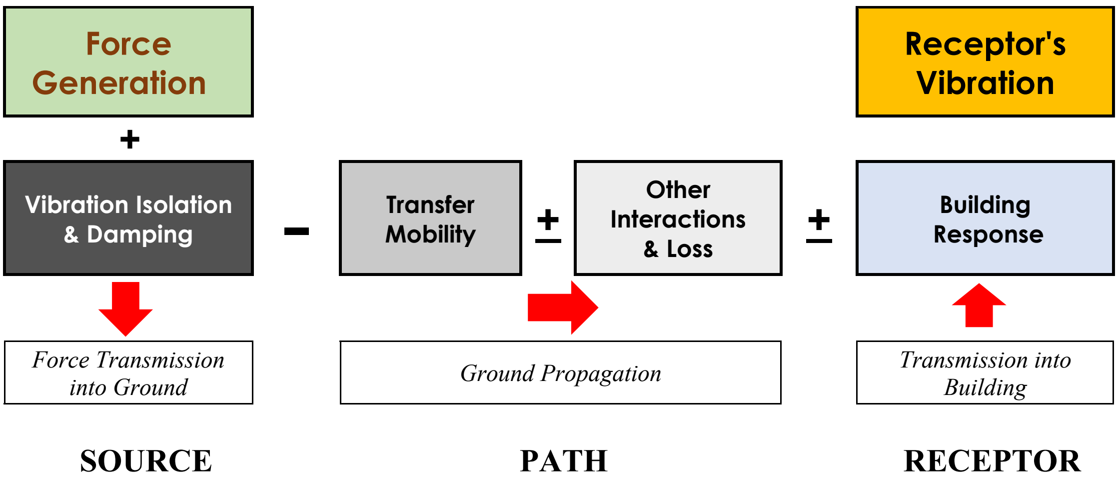


Figure E-1: Basic elements in vibration control

E-3 Controlling vibration at source

The most expedient and best practical means of vibration mitigation is to reduce vibration at source. This includes but not limited to:

(i) Choosing alternative lower impact equipment or work methods.
(ii) Routing, operating or locating high vibration sources as far away as possible from sensitive areas.
(iii) Sequencing operations so that vibration causing activities do not occur simultaneously (e.g., limiting number of concurrent piling).
(iv) Isolating the equipment and/or source causing the vibration on resilient mounts (vibration isolation).
(v) Use of vibration dampers for attenuation (damping) of vibration generated.
(vi) Keeping equipment well maintained.

Source specific vibration mitigation are reviewed below.

a. Construction

Strategies for managing and reducing vibration from construction sites include:

(i) Inform neighbors about the nature of the stages and anticipated duration of construction and vibration generating activities (e.g., excavation and rock-breaking, piling, etc.).
(ii) Use of alternatives to impact piling (e.g., rotary bored piling instead of driven or vibratory piling, oscillating method /reversed circulation drilling, press in piling, grip jacking, use of a hammer cushion when driving steel piles to minimize vibrations when impact hammer is used).
(iii) Selection demolition methods not involving impact where possible (e.g., hydraulic rock splitters instead of rock breakers)
(iv) Schedule demolition, earth moving and ground-impacting operations so as not to occur in the same time period.
(v) Avoid night time activities wherever possible.
(vi) Locate plant, equipment as far away as possible from the receptors.

b. Blasting

Reduction of the blasting induced vibration (and the corresponding air blast overpressures) severity requires either or combination of the following:

(i) Increase separation distance between receptors to blast site.
(ii) Decrease the quantity (weight) of explosives charge per delay.
(iii) Use of alternative tunnelling methods in lieu of drill and blast method (tunnel boring machine, road headers, excavator mounted rock saw, non-explosives excavation techniques e.g., penetrating cone fracture).
(iv) Ensure blast design is thorough and comply with best practice.
(v) Undertake precautions to minimize blast overpressure and fly rocks.

c. Roads

Practical means of vibration reduction for roads include:

(i) Reducing surface irregularities on roads such as potholes, uneven manhole covers, rumble strip and speed humps.
(ii) Restriction of heavy vehicles on particular roads
(iii) Limiting speed
(iv) Maintenance of roads and highways to prevent potholes and irregularities in road surface.
(v) Avoid using paver blocks at sensitive locations.

The most severe vibrations from road traffic are caused by heavy vehicles with stiff suspension moving rapidly along roads with irregular surfaces such as potholes, paver blocks and speed humps.

d. Railways

Common and most practical means of vibration reduction for railways involves:

(i) Use of continuous welded rails instead of jointed rail.
(ii) Use of rail isolation systems including resilient rail fastenings, under-sleeper pads, ballast mats and floating slabs.
(iii) Rolling stock control including regular maintenance (including truing of wheels to ensure roundness), and track maintenance (periodic rails grinding, etc.) to address deterioration in wheels and tracks that are inevitable with wear and tear.

Wheel and brake squeal and impact between wheels and track from out of roundness wheels are maintenance related issues and should be addressed with proper maintenance and upkeep of the trains (wheels in particular) and tracks (undulations / corrugations in the rails which shall require periodic rail grinding).

e. Industrial Plants

Practical means of vibration reduction in industrial plants and facilities involves:

(i) Select machines that are inherently have low vibration.
(ii) Machinery generating high vibrations should be supported on stiff structural supports installed with vibration isolators on inertia blocks.
(iii) Balancing, alignment and maintenance of plant and machinery.
(iv) Avoidance of vibration resonance in design and operations.

E-4 Controlling the transmission of vibration in the environment

Practical means of vibration reduction in the transmission path include:

(i) Increasing distance between source and sensitive receptors.
(ii) Trench (in ground vibration barriers).

Distance between source and receptors is one of the most effective mitigation measures against noise and vibration.

Geological conditions and terrain also have additional effect. Some studies have shown that annoyance from vibrations (for example from railways and piling) is inversely proportional to distance, with a rapid decrease from 25 to 150 meters and a slower rate of reduction over 200 meters, until no vibration disturbance is detected at 500 meters away (DUAP, 1997 cited in Assessing Vibration: A Technical Guideline, Dept of Environment & Conservation, NSW).

In principle trench (in ground barrier) may also be used for ground vibration reduction. Studies have shown that the depth of an inground vibration barrier has to be at least equal to one Rayleigh wavelength to achieve significant reduction (0.25 reduction factor). In case of traffic vibrations, the barrier (trench) has to be in excess of 10 meters because of the low frequency nature of these vibrations (Hunaidi, 2000).

E-5 Controlling vibration at the receptors

Controlling vibration at the receptors include:

(i) Land use planning.
(ii) Vibration isolation of the building structure.

Land use planning is the preferred proactive strategy with respect to infrastructure and industrial development planning. This includes gazette of buffer space and planning of non-sensitive or mixed development between vibration sources and sensitive receptors.

Controlling vibration at the receptors on a case by case situation can include vibration isolation of the building structure (whole building isolation similar to earth quake proofing of buildings) or part of the affected receptors space. Receptors.

E-6 Managing short term exceedance of recommended vibration values

In situations where short term vibrations exceed recommended vibration values, the reason of the exceedance need to be investigated, and corrective measures be undertaken where feasible.

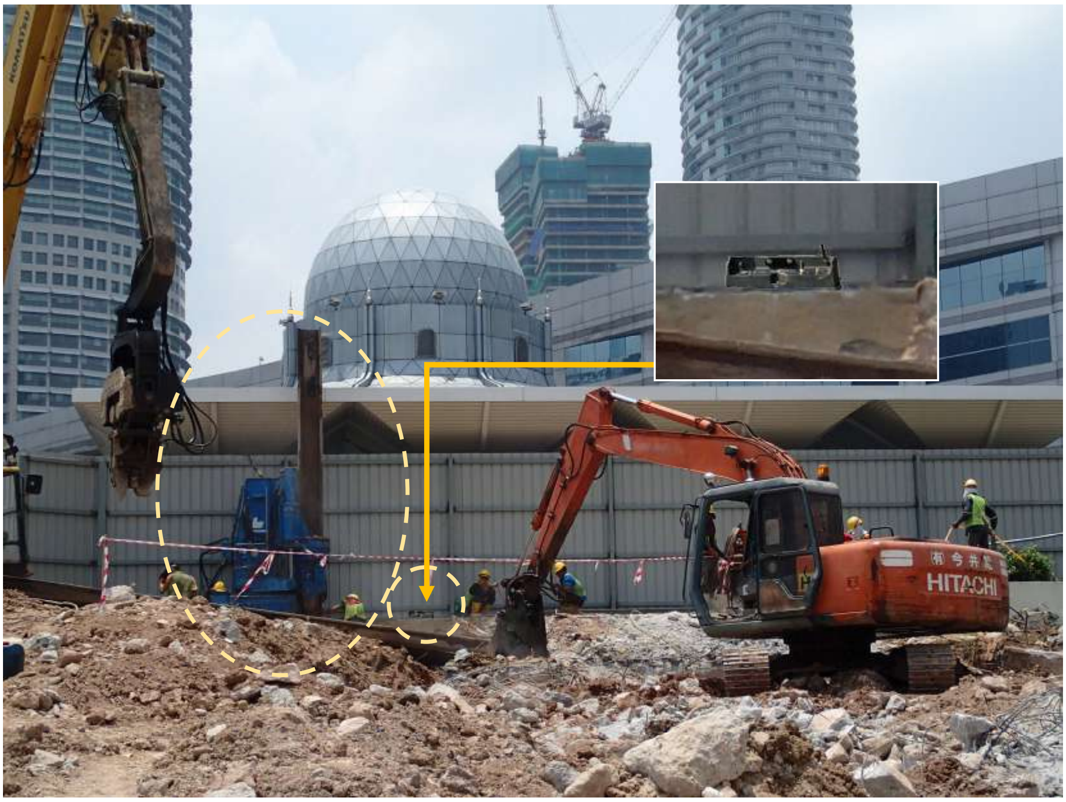
In some situations, the nature of the work and close proximity of receptors may still result in values exceeding recommending limits despite best practical means to reduce the vibration had been taken. In such situations the exceedance needs to be managed amicably between the party generating the vibration with the affected receptors though engagements.

E-7 Examples of vibration mitigation

Visual examples of vibration mitigation are presented in the following pages. The examples are for common sources in the environment i.e., construction (piling and demolition works) and road traffic. Industrial plants are more localized and shall be addressed at the industrial site.

The examples are not exhaustive; and additional guidance should be referred to technical literature.

Construction works represent the most common environmental vibration affecting the community with piling activities generating the most severe vibration (in addition to blasting works). Vibration monitoring and mitigation are usually required in construction (and demolition) works carried out adjacent sensitive receptors.



Source: Institute of Noise & Vibration, UTM

Plate E-1: Example of vibration monitoring and mitigation for construction works adjacent sensitive receptor: use of press in piles; and continuous vibration monitoring at property boundary of sensitive receptor (mosque) at KLCC, Kuala Lumpur.

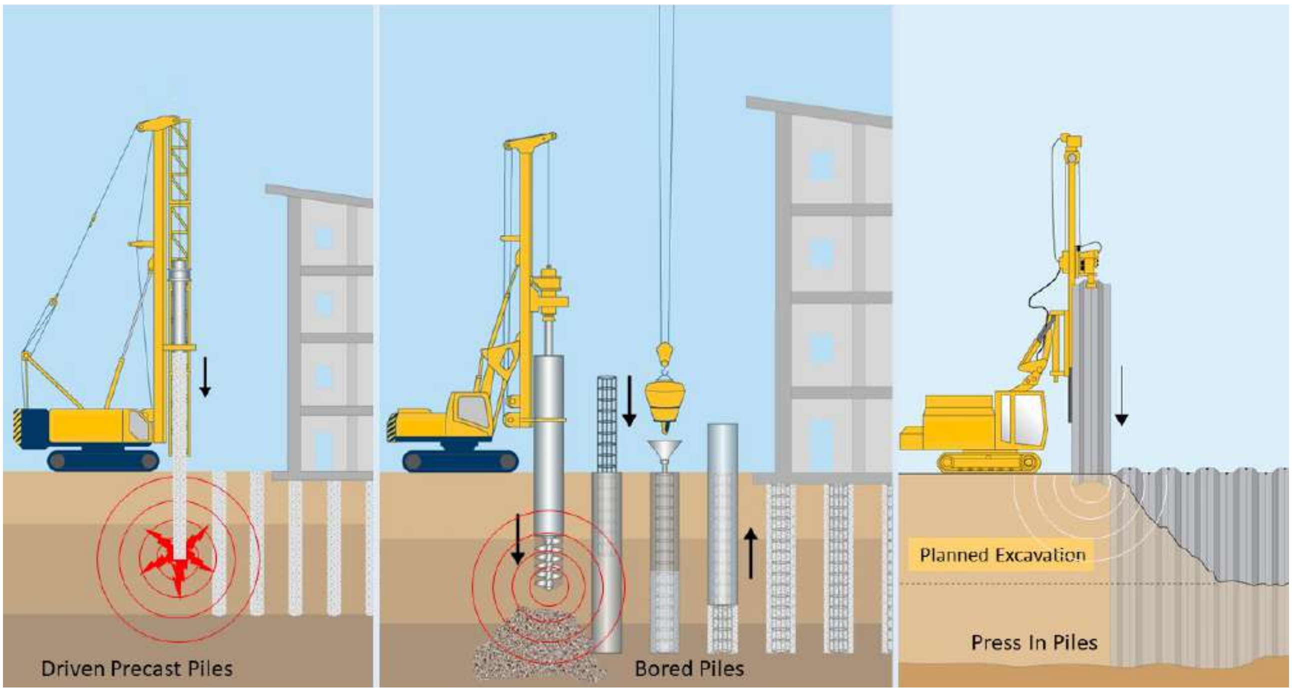
a. Construction

Plate E-1 above shows demolition and construction works in a new project development located adjacent sensitive receptors. The photograph shows continuous vibration monitoring at the construction site boundary as well as press in piling works in progress in addition to excavation (after demolition of an existing building.) Low impact vibration demolition and piling methods should be used.

Generic types of piles in common practice could be classified as: driven piles, bored piles and press-in piles as illustrated in Figure E-2. There are three driving systems that are applicable to both retaining and bearing piles: impact driving, vibro-driving and pressing. Non-driven systems are based on rotary bored piling using drilling and cast in situ methods. Variations to these generic piling types had evolved for specific applications including alternatives for low vibrations. Some typical (but not exhaustive) examples are presented here.

Drop hammer impact piling generates the highest vibrations and should not be used in built up areas. The use of drop hammer piling is in fact prohibited in some states and/or districts by the local authorities (Majlis Perbandaran, DBKL, etc.) in Malaysia. Chart D-1 in Annex D gives an example of drop hammer piling showing excessive vibration levels that are to be avoided.

Driven impact and vibro-driving piling of pre-cast friction piles are still in common use due to its simplicity and lower cost. Where such piling is permitted by the local authorities, the use of drop hammer and vibro-driven piling should only be used in locations that are sufficiently away from sensitive receptors or built up areas.



Source: Keller

Figure E-2: Illustration of three generic types of piling

Driven precast piles and sheet piles are installed using impact or vibration hammers to a required depth or resistance. The piles driving requires impactive forcing from impact or vibration hammers which inevitably result in significant ground borne vibrations.

Plate E-2 shows drop hammer piling in progress in a project site located away from sensitive receptors in relatively less developed areas. The precast piles are also evident in the photograph (placed on the ground pending use). Examples of impact hammering of precast RC pile and vibratory hydraulic hammering of sheet piles are shown in Plate E-3.

Bored piles are piles cast-in situ in the ground which requires boring (drilling) in the ground. Rotary bored piling generally results in lower ground vibrations as compared to impact and vibro-driven piles. Piling in built areas and adjacent sensitive receptors should be undertaken using rotary bored piles or other low vibration alternatives.

Examples of rotary bored piling are shown in as shown in Plate E-4 for buildings construction site. Plate E-5 shows another example for construction of elevated viaducts pier in an urban transit trains project.

While bored piles generally result in relatively lower vibration levels (as compared to impact driven piles), relatively higher vibration would still occur during drilling of hard strata, chiseling works and insertion of casing. Drilling through rock layers and obstacles requires the use of free-fall chisels which breaks the hard strata by means of percussive impact.

In situations where piling works are undertaken in close proximity to sensitive receptors, low vibration alternatives instead of conventional rotary drilling and chiseling shall be used. This includes continuous flight auger (CFA) piles and reversed circulation drilling (RCD) oscillatory methods. These alternatives result in significantly lower noise and vibration.

Examples of reversed circulation drilling are shown in Plate E-6 and Plate E-7.

Source: Institute of Noise & Vibration, UTM

Plate E-2: Example of hammer driven piling in progress (Kuching, Sarawak)

Plate E-3: Examples of (a) typical drop hammer impact pile driving of precast concrete pile; and (b) vibratory hydraulic piling of sheet pile

Pile penetration methods can be classified as either dynamic or static penetration method. Dynamic penetration method generates excessive noise and vibration due to the percussive or vibratory energy required. Press-in method piles are installed with static load generated from hydraulic rams and reaction forces. The press-in method results in significantly lower vibrations as compared to vibratory method.

Source: Institute of Noise & Vibration, UTM

Plate E-4: Rotary bored piling in an urban project site (KLCC Kuala Lumpur)

Source: Institute of Noise & Vibration, UTM

Plate E-5: Rotary bored piling in an urban transit rail project adjacent residential receptor (Klang Valley LRT3, Petaling Jaya)

Source: www.bumace.com

Plate E-6: Reversed circulation drilling in an urban underground train station work site (Kowloon, Hong Kong)

Source: Institute of Noise & Vibration, UTM

Plate E-7: Reversed circulation drilling for bored piles construction of piers in an elevated highway project (DUKE2, Sri Damansara Link) with noise & vibration monitoring in progress

Source: Giken Pte Ltd

Plate E-8: Pressed-in sheet piling using proprietary silent piler in urban work site

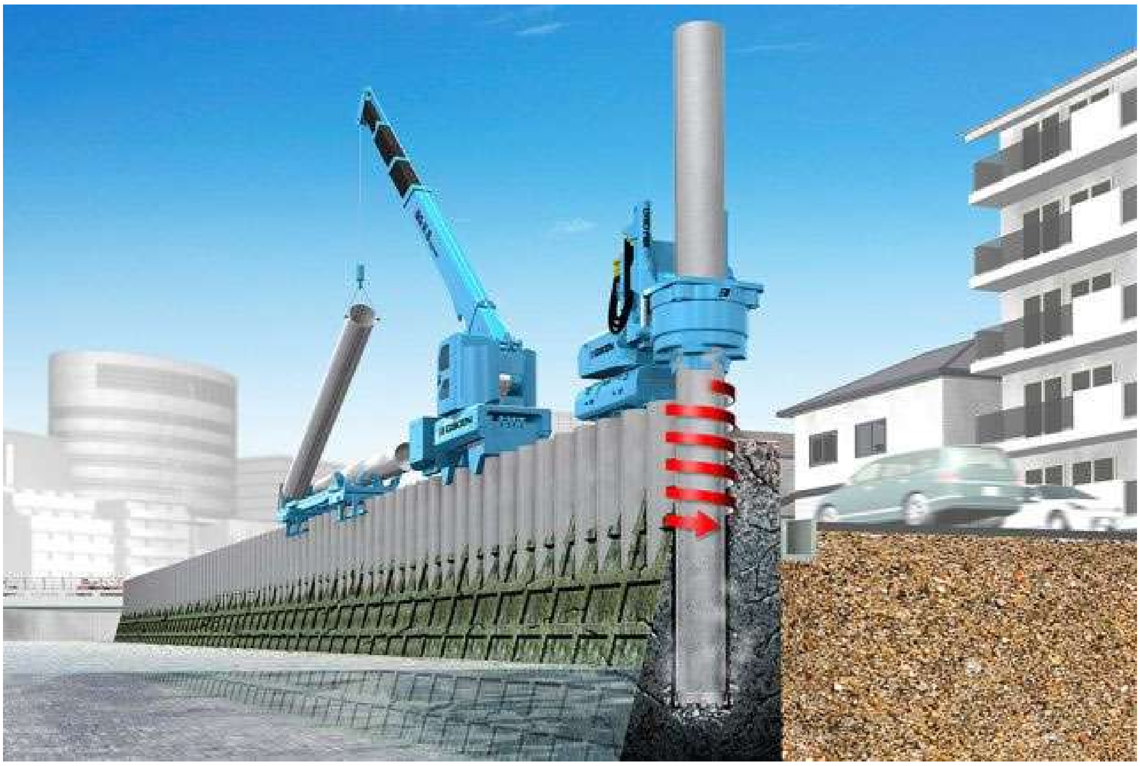
Source: Watson & Hill Ltd

Plate E-9: Pressed-in sheet piling using proprietary silent piler in marine work site

Sheet piles installed using vibratory hydraulic method is shown in Plate E-8 and Plate E-9. The press-in method for sheet piles generates significantly less vibrations as compared to the vibratory driven method shown (as in Plate E-3).

Source: www.giken.com

Plate E-10: Example of retaining wall construction using gyro press press-in piling method



Source: www.giken.com

Plate E-11: Gyro press method with pile penetration from press-in and gyration

Press-in method for tubular piles can be undertaken using the gyro press method involving press-in force and gyration force as shown in Plate E-10 and Plate E-11.

Source: www.abv.com.sg/bored micropile

Plate E-12: Example of bored micro-piling in a work site adjacent residential receptor

Source: www.abv.com.sg/ driven micropile

Plate E-13: Example of driven micro-piling in a congested sensitive work site

Micro-piling is an alternative to conventional piling typically used in congested (limited space or headroom) situations. Micropiles are small diameter bored cast-in situ piles that are bored or driven. Examples are given in Plate E-12 and Plate E-13. The piles being relatively smaller inherently result in lower noise & vibration.

b. Blasting and Rock Breaking

Source: knights-synergy.com/products-services/drill-blast services

Plate E-14: Optimal explosives (charge per delay) and rock removal in tunneling for blast induced vibration mitigation in tunneling project (NS2 Tunnel Singapore)

Source: knights-synergy.com/products-services/drill-blast services

Plate E-15: Controlled blasting in an urban condominium construction project (Singapore)

Source: Rocktek RocKraker

Plate E-16: Penetrating cone fracture gas expansion rock breaking alternative to rock blasting

Blasting induced vibrations are primarily governed by distance between blasting site and receptors, and quantum of explosives used.

The most effective mitigation for blasting induced vibrations for a given work site is to thus reduce the quantum of explosives used (maximum instantaneous charge) per delay. This however has to be balanced against material removed per blasting; and as such there is an optimal explosive charge and material removal in blasting works to be considered; Plate E-15.

There are non-explosive alternatives to rock blasting such as *penetrating cone fracture* (PCF), *Cardox* and *Nonox* which use a gas expansion (smokeless propellant) that when ignited, produces gas that fractures rock or concrete. An example is shown in Plate E-16.

Alternatives to conventional drill and blast method in tunnelling works using mechanical excavation methods result in lower vibration level than blasting. This includes road header and crawler excavator (excavator with mounted saw).

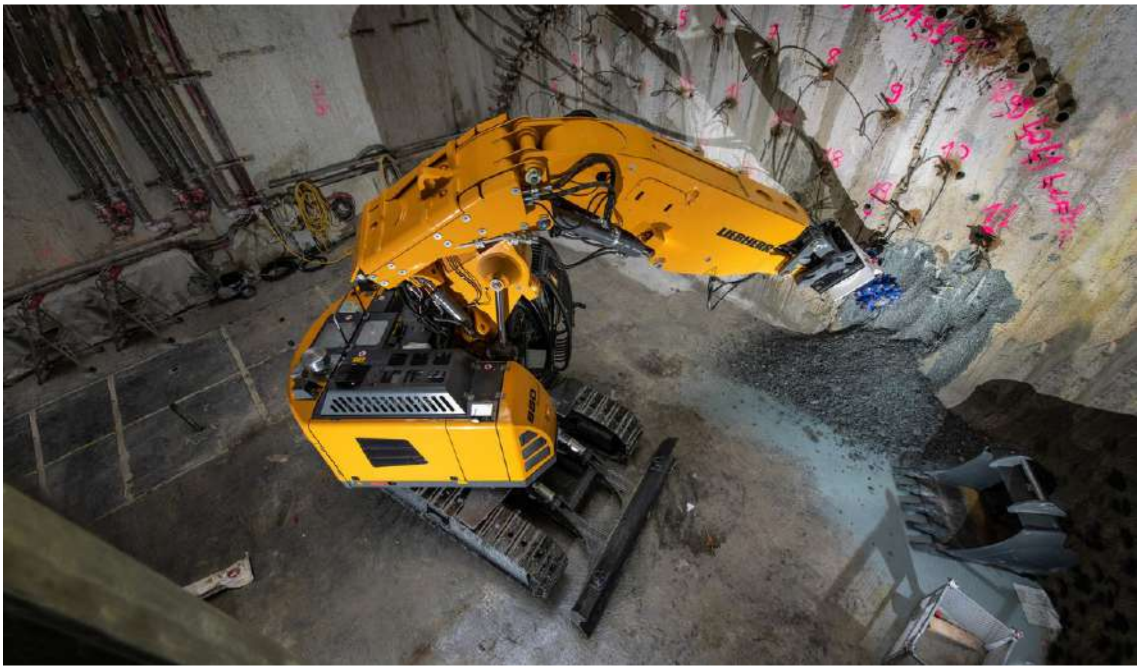
A road header is an excavating equipment consisting of a boom-mounted cutting head, a loading device usually involving a conveyor, and a crawler travelling track to move the entire machine forward into the rock face in tunneling. Plate E-17 and Plate E-18 shows examples of road headers and its use in tunneling works. Plate E-19 and Plate E-20 shows examples of crawler excavators and its use in rock cutting.

Source: https://crossriverrail.qld.gov.au/construction/roadheaders/

Plate E-17: Road-header used in underground railway tunnelling works (Cross River Rail, Australia)

Source: www.geoplus.co.uk/news/first-road-header-launched-for-melbourne-metro-tunnel-29-11-2018/

Plate E-18: Example of road-header used in metro tunnelling works (Melbourne Metro)



Source:https://www.lectura-specs.com/en/model/construction-machinery/crawler-excavators-liebherr/

Plate E-19: Example of crawler excavator used in underground tunnelling works

Plate E-20: Rock cutting work in progress in an underground metro project (Australia)

c. Road Traffic Vibrations

Plate E-21: Common source of road traffic vibrations

The most expedient measure for mitigation of road traffic induced vibrations is to prevent the occurrence of the vibrations. The most common causes of road traffic vibrations are potholes and manholes, Plate E-21. This requires inspection and maintenance of roads and manholes by the relevant parties.

The other common cause of road vibrations are irregularities on the roads such as speed humps, rumble strips (Plate E-21), paver blocks at road junctions (instead of bitumen), large discontinuities and expansion joints in elevated highways.

While rumble strips and speed humps are usually used for road safety and to enforce speed limits, such it should be used sparingly at locations in close proximity to sensitive receptors.

Use of paver blocks on roads, including traffic light junctions along main roads where vehicles would inevitably travel at speed, in close proximity of sensitive receptors should consider potential impact for road traffic vibrations.

d. Railways and Transit Trains

Source: www.pandrol.com/product/under-ballast-mats/

Plate E-22: Ballast mat for railway tracks vibration isolation

Source: www.pandrol.com/product/under-sleeper-pads/

Source: Stjepan Lakusic, University of Zagreb   *Source: www.gupta-verlag.com/news/technology*

Plate E-23: Under sleeper pads vibration isolation of railway tracks

Source: www.delkorail.com/products/rail-products/egg.htm

Source: www.pandrol.com/product/vanguard

Plate E-24: Resilient fastening systems for tracks vibration isolation

The most expedient mitigation of railways vibrations is to avoid or minimize the vibration generation in the first instance followed by mitigation to reduce the vibration propagation. In this respect the mitigation measures listed in order of importance are:

(i) Use of continuous welded tracks.
(ii) Regular inspection and maintenance of wheels (truing works to remove flat spots and restore wheels roundness).
(iii) Regular inspection and maintenance of tracks (acoustic grinding of tracks).
(iv) Trackworks vibration isolation.

Source: www.pandrol.com/product/floating-slab-mat/

Plate E-25: Floating slab track using mat isolation

Railway tracks vibration isolation involves the use of resilient vibration isolation mats or devices installed between the rails, or slab supporting the rails with the underlying structure or ground. Different vibration isolation mats and systems are available for ballasted tracks (rails secured onto sleepers installed onto ballast bed), and slab tracks (rails secured directly onto concrete slab). Interstate railways in Malaysia are typically ballasted tracks and urban transit trains are slab tracks.

Vibration mitigation of ballasted tracks are with the use of ballast mat as shown in Plate E-22; or alternatively with under sleeper pads as shown in Plate E-23. Under sleeper pads are more amenable to replacement and retrofits of existing operational railways. Ballast mats are usually done during construction of new railways, or during replacement of ballast and rails in existing railway lines.

Rails in slab track are as a matter of standard practice installed directly onto the slab (direct fixation) with rigid baseplates or resilient baseplates (with nominal vibration attenuation properties). Trackwork vibration isolation involves the use of resilient fastening systems with higher vibration attenuation (trackworks isolation upgrade) typically required for railways in proximity to sensitive receptors. Different proprietary resilient fastening systems are available with varying range of vibration reduction performance. Examples of typical resilient fastening systems are shown in Plate E-24.

In critical situations, floating slab tracks (FST) may be appropriate, Plate E-27. Floating slab tracks involve the use of vibration isolation mats as shown in Plate E-25; or with use of discrete vibration mounts as shown in Plate E-26. Experience elsewhere in the world had shown that floating slab tracks are not readily amenable to inspection and replacement without substantial service disruptions; and as such its use have to be balanced against conflicting design, construction, maintenance, and operational constraints.

Source: https://learning legacy.crossrail.co.uk/

Plate E-26: Floating slab track using discrete isolation mounts - under construction with rebars and vibration isolators installed awaiting concrete pour (Crossrail, United Kingdom)

Source: Adam Brunskill. Floating slab track - Chatswood

Plate E-27: Newly completed floating slab track (Chatswoods Station, Sydney)

e. Industrial Plants and Machinery

Source: Institute of Noise & Vibration, UTM

Plate E-28: Vibration isolator and viscous dampers installed in industrial facilities

Vibration concerns and propagation from industrial plants and machineries tend to be localized at the locations of plants and machineries. Mitigation as a matter of best practice involves use of vibration damping and isolation devices installed at the vibration source. Examples of typical vibration isolators and viscous dampers installed in industrial plants are shown in Plate E-28.

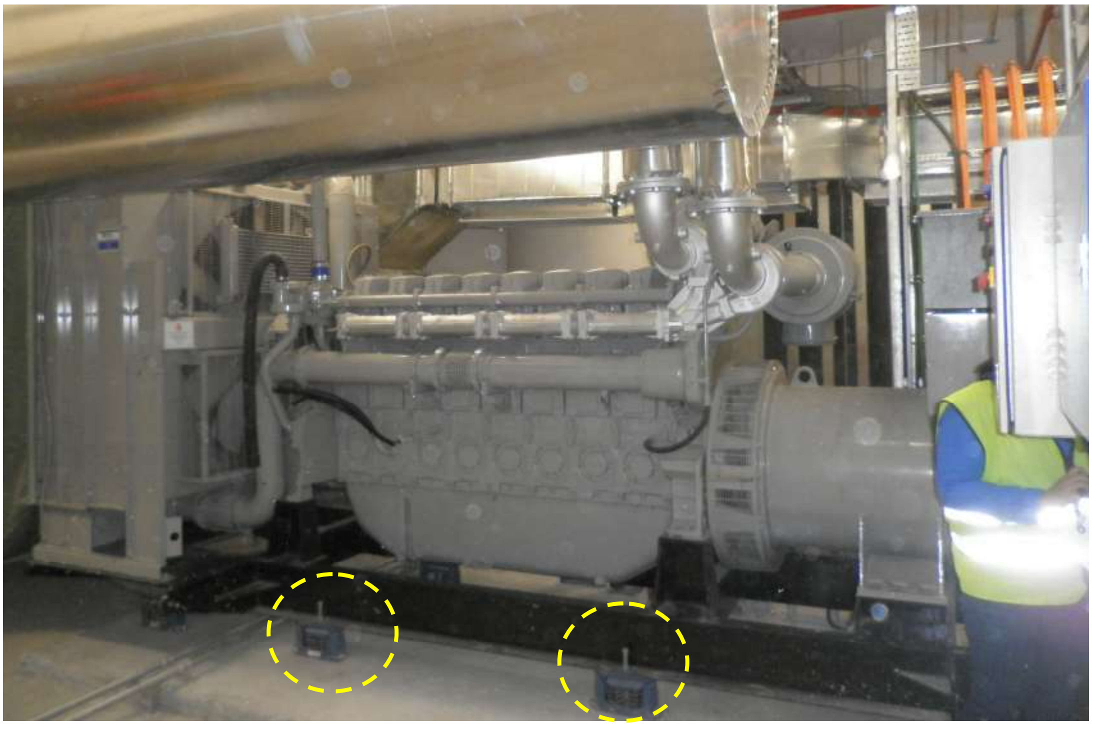
Source: Institute of Noise & Vibration, UTM

Plate E-29: Examples of vibration isolators for cooling towers

Examples of vibration isolators used for vibration isolation of cooling towers (typically used in industrial plants and buildings) are shown in Plate E-29.

Source: Institute of Noise & Vibration, UTM

Plate E-30: Example of vibration isolators for generators



Source: Institute of Noise & Vibration, UTM

Plate E-31: Example of vibration isolators for generators

Examples of vibration isolators used for vibration isolation of pump sets are shown in Plate E-30, and for generators shown in Plate E-31. Such installations are typical in industrial plants (indoors and outdoors installation) and inside buildings.

ANNEX F

STATUTORY INSTRUMENTS, STANDARDS AND OTHER GUIDANCE

Statutory instruments in Malaysia

Environmental Quality Act 1974.

Environmental Quality Act (Amendment) 1985.

Mineral Development Act 1994. Mineral Development (Blasting) Regulations 2013.

Standards

ISO 2631-1:2003 – Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 1: General requirements.

ISO 2631-2:2003 – Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 2 Vibrations in buildings (1 to 80 Hz).

ISO 2631-3: 1985 – Evaluation of human exposure to whole-body vibration – Part 3: Evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0.1 to 0.63 Hz.

BS 7385-2: 1993 - Evaluation of human exposure to whole-body vibration – Part 2: Guide to damage levels from groundborne vibrations

BS ISO 4866: 2010 – Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and evaluation of their effects on structures

BS 6472-1:2008 – Guide to evaluation of human exposure to vibration in buildings – Part 1: Vibration sources other than blasting

BS 647221:2008 – Guide to evaluation of human exposure to vibration in buildings – Part 1: Blasting-induced vibration

BS 5228-2:2009+A1:2014 – Code of practice for noise and vibration control on construction and open sites – Part 2: Vibration

DIN 4150-3:2016-12 – Vibrations in buildings – Part 3: Effects on structures.

Guidelines

FTA Report No.0123. Transit noise and vibration impact assessment manual, Federal Transit Administration, September 2018.

Australian and New Zealand Environment and Conservation Council. Technical basis for Guidelines to minimize annoyance due to blasting overpressure and ground vibration, September 1990.

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