Construction noise and vibration impact on sensitive premises

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ABSTRACT

Construction noise and vibration must be considered an essential part of the development of any transportation facility. Road and tunnel construction is often conducted in close proximity to residential and commercial premises and should be predicted, controlled and monitored in order to avoid excessive noise and vibration impacts. Construction noise and vibration can threaten a project's schedule if not adequately analysed and if the concerns of the community are not addressed and incorporated.

AIRBORNE NOISE

Construction over the length of a project can take place 24 hours a day and for major projects, in excess of 2 to 3 years. Construction equipment can operate in very close proximity to residential and commercial (and even industrial) premises. Many items of equipment can be found operating at any time throughout a project. Equipment types range from mobile cranes, pile drivers, jackhammers, dump trucks, concrete pumps and trucks, backhoes, loaders, dozers, rock-breakers, rock drills, pile boring machines, excavators, concrete and chain saws, and gas and pneumatically powered hand tools.

An additional factor of great importance is the presence of low frequency noise (< 200 Hz) in the source sound spectra of many items of equipment for which the 'true' annoyance capability at sensitive receptors is not reflected either in the measurement or prediction using the overall A-weighted sound pressure level, or dB(A).

GROUND VIBRATION

The total attenuation of vibration from an item of construction equipment to a receptor is estimated from the spreading loss, a value dependent on whether the source of vibration is considered a point, line or planar source, attenuation due to internal losses in the soil and rock, being a function of loss factor η, velocity of propagation c, frequency of the vibration and distance to the receptor and attenuation due to changes in soil or rock along the propagation path, being a function of mechanical impedances of individual differing rock components. Mechanical impedance is derived from the density of the various media and longitudinal wave speeds for each media.Wave propagation is usually surface or Rayleigh (or R-wave) type. Here again the perception of ground-borne vibration outside and especially inside premises is of a low frequency character.

This paper describes methods adopted to estimate the overall noise level and airborne spectra at the boundary of sensitive premises and within these premises using various software modelling packages applied to a typical road making construction project. The indoor receptor levels are then compared to acceptable criteria. Ground-borne vibration at the boundary of premises is compared to established vibration perception evaluation criteria.

INTRODUCTION

Construction noise and vibration issues must be considered an essential part of the assessment of the development of any transportation facility. Road and tunnel construction is often conducted in close proximity to residential and commercial premises and associated noise and vibration should be predicted, controlled and monitored in order to avoid excessive noise and vibration impacts. Construction noise and vibration can threaten a project's schedule if not adequately analysed and if the concerns of the community are not addressed and incorporated.

In general a project's schedule can be maintained by balancing the type, time of day and duration of construction activities: adhering to local or state noise control requirements and being proactive to community concerns.

Airborne noise

Construction over the length of the project can take place 24 hours a day. Construction equipment can operate in very close proximity to residential and commercial premises. Many items of equipment can be found operating at any time throughout the project. The full gambit of equipment types are used such as mobile cranes, pile drivers, jackhammers, dump trucks, concrete pumps and trucks, backhoes, loaders, dozers, rock-breakers, rock drills, pile boring machines, excavators, concrete and chain saws, and gas and pneumatically powered hand tools.

Typical construction equipment is shown in Figure 1.

Figure 1. Typical construction equipment

Source: (FHWA 2006)

Noise control specifications can contain both relative noise criteria limits at identified noise sensitive receptor locations, as well as absolute noise emission limits for all equipment used on site. The noise specification boundary line criterion is primarily a relative criterion in which construction-induced

L_{Aeq} noise levels in general cannot exceed baseline (pre-construction) L_{Aeq} noise levels by more than 5 dB at identified noise sensitive receptor locations. While an increase of 5 dB may be noticeable, it should not present an unacceptable noise hardship condition.

Baseline L_{Aeq} noise levels must be established prior to construction operations in accordance with the draft Construction Noise and Vibration Code (*CNVC 2009*) which requires collection of at least two non-consecutive weekday 24 hour noise readings as well as one Sunday noise reading at specified noise receptor locations throughout the construction area. These baseline L_{Aeq} noise readings are then reduced into daytime, evening, and night-time average levels and used to establish boundary line noise criteria limits by adding 5 dB, or by defaulting to the higher L_{Aeq} option (where existing background ambient noise level exceeds the standard noise limits) during the relevant time period specified in the Noise Code.

Standard noise limits for general construction during restricted hours at residential receptors are given in Table 1.

Time Period	General construction activities $L_{Aeq,15min}$ dB(A)		
	Duration of Activity		
	Short term	Medium term	Long term
Daytime, restricted hours	65	60	55
Evening period, 6.00pm to 10.00pm, on any day	60	55	50
Late night/early morning period, 10.00pm to 7.00am on any day.	45	45	45

Table 1. Standard noise limits for restricted hours

Restricted hours means the period between 6.00pm and 7.00am Monday to Friday and 1.00pm to 12.00 midnight Saturday and at any time on a Sunday or a Public Holiday. Standard working hours allow noise limits 10 dB(A) greater than those presented in Table 1 for medium to long term activities.

Short term construction and maintenance activities are those which would affect any one noise or vibration sensitive site for up to 14 days, medium term for more than 14 days and up to 20 weeks while long term activities exceed 20 weeks but less than18 months.

An absolute noise criterion is applied to generic classes of heavy equipment to limit their noise emission levels. Equipment specific A-weighted L_{Amax} noise limits in dB(A) expressed at a reference distance of 15m are defined in the Noise Code similar to those given in Table 2.

Equipment Description	Sound Power Level dB(A) re. 1 picowatt	L_{Amax} noise limit at 15m, dB(A)	Acoustic Usage Factor %
Blasting	125	94*	1
Crane (mobile or stationary)	116	85	16
38t Bulldozer	118	87	40
Impact Pile Driver (diesel or drop)	126	95*	20
Rock drill	116	85	20
Dump truck	115	84	40
35t Excavator	114	83	40
Rock-breaker	120	89	20
Front end loader	111	80	40
Grader	116	85	40

Table 2. Typical construction equipment noise emission criteria limits

*Indicates impactive device

These emission limits are achievable but are conservatively set as low as possible in order to require equipment to be well maintained, and often requires some form of source noise control. Each and every item of equipment should be pre-certified by the contractor's acoustical engineer to pass their respective 15m noise emission limit before the equipment is allowed to work on site.

The 'Acoustic Usage Factor' represents the percentage of time that a particular item of equipment is assumed to be running at full power while working on site. The influence of idling noise may be disregarded when the difference between the operating equipment noise and the idling noise is more than 10 dB(A).

Thus, a contract specification can include two types of noise criteria limits, relative boundary line limits and absolute equipment emissions limits, both of which should be complied with by the contractors at all times. Consequently, if measured or anticipated construction noise limits exceed the allowable noise criteria limits, then noise mitigation measures are warranted and must be implemented prior to and maintained during associated work activities.

An added concern is that of the impact of low frequency noise (<200 Hz) especially inside residential properties. The traditional methods of using L_{Aeq} and L_{Amax} are not appropriate for such situations. This paper applies the draft Ecoaccess Guideline 'Assessment of Low Frequency Noise' (*LFN 2008*) to assess the impact of low frequency noise from earthmoving equipment and the criteria set out in this document.

PREDICTION METHODS

Broadband noise

Noise levels at receptor locations can be calculated by using accepted point-source strength propagation algorithms such as that below, summed over all operating equipment:

$$L_{Aeq,15min} = L_{Amax,15m} - 20\log_{10}(d/15) + 10\log_{10}(U.F.\%/100) - IL_{bar} - 10G\log_{10}(d/15),\ dB(A) \quad (1)$$

where $L_{Amax,15m}$ is the A-weighted noise emission limit for the equipment at 15m (see Table 2).

d = distance between the equipment and the receptor in m

U.F.% = time averaging equipment usage factor in % (see Table 2)

ILbar = A-weighted insertion loss of any intervening barrier/screen/enclosure, computed separately in dB(A)

G = ground factor constant due to topography and ground effects

For sound transmission over hard earth, G = 0

Source: (FHWA 2006)

Case Study Scheme

A scenario is chosen to include a range of earthworks operations and construction plant. The plant used in the study were a twin-engined motorized scraper, off-highway dump truck, bulldozer, excavator and front end loader. The noise is propagated over hard earth and there are no intervening barriers. Earthworks is likely to occur for 4 months (medium term). A prediction is made of $L_{Aeq,1h}$ external to an apartment located 30m away from the centre of construction operations.

Predictions at this location are presented in Table 3.

Operation	Plant Type	$L_{Amax,15m}$	Acoustic Usage Factor %	Process L_{Aeq}
Drive-by on haul-road	Caterpillar 657B scraper	85	40	83
Earthworks	Front end loader	80	40	78
Earthworks	Dump truck	84	40	82
Earthworks	Bulldozer	87	40	85
Earthworks	Excavator	83	40	81
			Total $L_{Aeq,1h}$	89

Table 3. Prediction of noise level at apartment from earthmoving operations

Low frequency noise

The internal overall dB(A) and low frequency (LF) noise climate within a typical apartment building was determined from the sound insulation properties of two typical space-dividing building elements comprising the external façade and from the sound absorptive properties of internal treatment of the apartment. Other noise attenuation measures like temporary external barriers close to operating equipment and treated construction plant and equipment were not considered in this determination.

The frequency spectra of the construction equipment in terms of $1/3^{rd}$ octave band levels and overall dB(A) was established by considering the following sources of information : (*TRRL 1976*) and (*CC&AA 2005*).

The results of this information as source spectra for construction equipment in $1/3^{rd}$ octave bands Z-weighting, overall dB(Z) and dB(A) in terms of $L_{Aeq,2min}$ is presented in Table 4. Z-weighting is defined in IEC 61672-1, the latest international standard for sound pressure level measurements. It stands for zero-weighting, or no weighting; i.e., a flat measurement with equal emphasis of all frequencies.
A sampling period of 2 minutes was adopted for this LFN investigation as source data was reported for this time period.

1/3rd octave band frequency (Hz)	Excavator on stockpile @10m	Front end loader driving @10m	Caterpillar Scraper Unsilenced @15m
31.5	89	95	86
40	93	101	83
50	96	100	76
63	96	106	83
80	104	108	103*
100	104	108	87
125	97	115	82
160	100	106	81
200	100	107	82
250	100	108	75
dB(Z)	112	120	103
dB(A)	106	114	90

* Indicates prominent tonality

Table 4. Source spectra and overall noise levels

For predictions of building component sound reduction and average absorption coefficients within living areas the spectra from Table 4 was adopted demonstrating the greatest sound energy within the 50 Hz to 250 Hz 1/3rd octave bands, as these frequencies are the most prominent (and probably the most annoying), and sometimes exhibit a characteristic tone (as demonstrated by the Caterpillar Model 631B scraper). The overall Z and dB(A) values were measured or derived from the full audio frequency range of 31.5 Hz to 10 kHz, although not all of these frequency bands are reported in Table 4. The items of construction equipment chosen for the prediction of LF intrusion were the front end loader driving at 10m (Figure 2), the excavator (Figure 3) and the scraper operating at 15m (Figure 4).

Figure 2. Front end loader

Source: (CEN 1985)

Figure 3. Hydraulic excavator and 77 tonne truck

Source: (Griffin Coal 1982)

Figure 4. Caterpillar Scraper

Source: (CEN 1985)

Noise Propagation and NR estimation

Internal noise levels were calculated based upon point source emission, free field sound propagation, external façade noise attenuation and average absorption coefficients for internal treatments. Determinations of the noise reduction (NR), overall dB(A) rating and Z-weighted spectra within an apartment then require complex calculations within each of 18 1/3rd octave frequency bands over the range of 100 Hz to 5kHz. Calculations of the sound reduction for the additional three centre frequencies - 50, 63 and 80 Hz were derived from the mass law for homogenous panels and the double panel with connections theory.

For this reason four independent computer programs developed as Excel spreadsheets were used to determine:

- the LF noise attenuation of the three sources of construction equipment over distance
- the sound reduction within 1/3rd octave bands of an external partition composed of different building elements eg. wall, windows and doors with different areas
- the average sound absorption coefficients of various internal building elements and surface treatments within 1/3rd octave bands, assuming even distribution of absorbing material and neglecting air absorption, and

- the noise reduction through the building facade, internal Z-weighted sound pressure levels as a function of frequency, the overall equivalent sound pressure level, $L_{Aeq,2min}$ and low frequency descriptor, LpALF

Characteristics of sensitive premises

An apartment living area, in this case a bedroom of typical dimensions with a single window incorporated, was assumed. The dimensions of the bedroom facing the three noise sources were taken as 4.6m (L) x 3.8m (B) x 3m (H) with a floor surface area of 17.5m^2. The dimensions of the room were taken in the ratio 1(H) : 1.28 (B) : 1.54 (L) in order to achieve maximum sound diffusion within the room, to distribute modal frequencies in the best way and so avoid resonance modes which might occur at the dominant low frequencies in the three construction equipment noise signals.

The window size was taken as 10% of the floor area or 1.75m^2 and a standard window size of 1.5m (B) x 1.2m (H) adopted in computer modelling.

Choice of building components

Two external building materials were chosen, based on their STC (or R_W rating) and sound reduction predominantly at the low frequencies of 50 Hz to 200 Hz. Internal treatments were also selected based on a high noise reduction coefficient (NRC) and absorption coefficients over the frequency range from 50 Hz to 160 Hz.

Two scenarios were set up in terms of composite building elements in the external façade and internal absorption treatments. The computer models were then run each time with the aim of achieving the highest noise reduction in terms of dB(A). At the same time, checks were made as to the noise reduction achieved within the 50 Hz to 200 Hz 1/3rd octave frequency bands compared with LF noise limits. The configurations were chosen in an attempt to compare the maximum dB(A) and LF noise reductions achieved for the two configurations.

Internal noise levels

The predicted internal noise levels were compared to: a sleep disturbance criterion of 35 dB(A) L_{Aeq} for steady noise, auditory perceptions in terms of Z-weighted sound pressure level versus 1/3rd octave frequency bands, annoyance rating for non-tonal, low frequency noise in the domain less than 160 Hz using descriptor L_{pALF} and; annoyance assessment for tonal noise exhibited by the scraper at centre band 80 Hz.

SELECTED SCENARIOS

The following two combinations of building elements and absorptive treatments were selected for modelling:

Combination #	Description of materials	Noise reduction coefficient (NRC)	Absorption coefficient at 125 Hz
R1 (*Stramit 1984*)	Ceiling: Stramit/Woodtex 50mm coarse grain No 11 panel	0.57	0.5
	Walls:Stramit/Woodtex 50mm coarse grain No 11 panel	0.57	0.5
(*EBS 1973*)	Window: EBS Ref No. 7020-4 10-76-13mm	0.15 (est)	0.35
(*Mec Eng 1982*)	Floor: Heavy carpet on 40 oz hairfelt or foam rubber laid on concrete	0.55	0.08
R5 (*Stramit 1984*)	Ceiling : Stramit Roof and Ceiling System Refer SA.17. Other components as for R1 but no window	1.02	0.65

Table 5a. Combinations of building elements and absorptive treatments – receiving area

Combination #	Description	R_W	Sound reduction at 125 Hz
P1 (*EBS 1973*)	Wall: EBS Ref No. 6107. Clay bricks, rendered 13mm both sides	45	33
(*EBS 1973*)	Window: EBS Ref No. 7020-4, 10-76-13mm spacing	46	36
P5 (*CSR Man*)	Wall: CSR Gyprock Masonry–Wall System. No.721 with no window	67	50

Table 5b. Combinations of building elements and absorptive treatments- dividing partition

Ground vibration

Wave propagation is usually surface or Rayleigh (or R-wave) type (*CALTRAN 2004*). Most energy is transmitted in the R-wave which is the most significant disturbance along the surface of the ground, and it may be the only clearly distinguishable wave at large distances from the source. Accordingly, propagation of vibration from construction sources, including pile driving, is typically modelled in terms of R-waves.

The perception of ground-borne vibration within premises is of a low frequency character. Typical vibration from transportation and construction sources falls in the range of 10-30 Hz and usually centres around 15 Hz. Vibratory pile drivers generate continuous vibrations with operating frequencies typically between 25 and 50 Hz. Vibratory rollers operate in the range 26 to 66 Hz (high setting) and 26 to 55 Hz (low setting). (*CALTRAN 2004*). For the purposes of assessing vibration effects on people and structures, use of a frequency-independent material damping coefficient is supported by the fact that damage levels in terms of velocity in the frequency range of 1-80 Hz tend to be independent of frequency.

VALUES OF VIBRATION VELOCITY

Table 6 presents typical values of vibration for some construction equipment sources in terms of peak particle velocity (ppv) expressed as mm/sec.

Equipment	Reference ppv at 7.6m (mm/sec)
Impact pile drivers	16.5
Vibratory roller, speed 1.5 to 2.5 km/h	5.3
Large bulldozer	2.3
Loaded trucks	1.9

Table 6. Values of vibration velocity for construction equipment sources

Source: CALTRAN 2004

VIBRATION PREDICTION FOR CONSTRUCTION EQUIPMENT

Vibration prediction originally uses equations based on imperial units (*CALTRAN 2004*) – feet, inches/sec and rated energy of equipment in ft-lbs. Conversions have been made to the corresponding metric units viz. metres, mm/sec and joules.

Impact pile drivers

The peak particle velocity (ppv) from impact pile drivers can be estimated by the following equation:

$$ppv_{\text{impact pile driver}} = ppv_{ref}(7.6/D)^n \times (E_{equip}/E_{ref})^{0.5} \text{ (mm/s)} \quad (2)$$

where:

ppv_{ref} = 16.5mm/sec for a reference pile driver at 7.6m

D = distance from pile driver to the receiver in m

E_{ref} = 48,852 Joules (rated energy of reference pile driver)

E_{equip} = rated energy of impact pile driver in Joules

n = 1.1 is a value related to the vibration amplitude rate through ground.

Vibration impact estimates may be refined further by using values of 'n' that are based on soil type classification or soil conditions at a site as illustrated in Table 7.

Description of soil material	n, slope or attenuation rate or composite value for geometric and material damping
Weak or soft soils: loose soils, mud, loose beach sand, dune sand, recently ploughed ground, top soil (shovel penetrates easily)	1.4
Competent soils: most sands, sandy clays, gravel, silts, weathered rock (can dig with a shovel)	1.3
Hard soils: dense compacted sand, dry consolidated clay, some exposed rock (need a pick to break up)	1.1
Hard, competent rock: bedrock, freshly exposed hard rock (difficult to break with hammer)	1.0

Table 7. Measured and suggested 'n' values based on soil class

Other construction equipment (bulldozers, excavators and rollers etc)

The peak particle velocity (ppv) from other construction equipment can be estimated by the following equation:

$$ppv_{equipment} = ppv_{ref}(7.6/D)^n \text{ (mm/s)} \quad (3)$$

where:

ppv_{ref} = reference ppv at 7.6m (see Table 7)

D and n as previously defined.

RESULTS

Broadband sound

The overall noise determined as $L_{Aeq,1h}$ 89 dB(A) from the earthmoving operations exceeded the prescribed noise levels during restricted hours (Table 1) by as much as 29 dB(A) during the day and as much as 34 dB(A) during the evening period.

Low frequency sound

The results of the predictions using four computer models are presented in Table 8a, 8b and 8c. The results are presented in terms of the noise reduction achieved, the internal A-weighted equivalent sound pressure level, $L_{Aeq,2min}$ and the low frequency descriptor, L_{pALF}. A muffler with an insertion loss of 12 dB at centre frequency 80 Hz fitted to the scraper to remove tonality was also modelled for L_{pALF} in addition to the rating method for tonality according to the Ecoaccess LFN Guideline (*LFN 2008*). The internal ambient noise level is modelled for external ambient noise levels of 104 dB(A), 97 dB(A) and 84 dB(A) corresponding to the front end loader, excavator and scraper as estimated at 30m, respectively (Tables 9a, 9b and 9c).

Combinations	NR, dB(A)	$L_{Aeq,2min}$ dB(A)	L_{pALF}
R1 + P1	46	58	54
R5 + P5	60	44	44

Table 8a. Internal noise levels and NR for two combinations due to front end loader at 30m, 104 dB(A) $L_{Aeq,2min}$

Combinations	$L_{Aeq,2min}$ dB(A)	L_{pALF}
R1 + P1	51	45
R5 + P5	39	39

Table 8b. Internal noise levels for two combinations due to excavator at 30m, 97 dB(A) $L_{Aeq,2min}$

Combinations	$L_{Aeq,2min}$ dB(A)	L_{pALF} dB
R1 + P1	34	33
R5 + P5	28	28

Table 8c. Internal noise levels for two combinations due to scraper at 30m, 84 dB(A) $L_{Aeq,2min}$

Prediction of impacts of ground vibration

Ground vibration has been predicted at a distance of 30m (as previously estimated for airborne sound) from construction equipment in velocity, mm/s as shown in Table 9. The distances required for each item of equipment to achieve an acceptable annoyance criteria (strongly perceptible) of 2.5 mm/s (*CALTRAN 2004*) for continuous vibration and hard, competent rock is also shown.

Equipment Type	Equipment Rating or Energy	'n' value and soil type				Distance to achieve acceptable annoyance criteria (m)
		n = 1.0	n = 1.1	n = 1.3	n = 1.4	n = 1.0
		Hard, competent rock	Hard soils, dense compacted sands	Competent soils, most sands, gravel	Weak or soft soils, top soil	Hard, competent rock
		30m	30m	30m	30m	Acceptable
Impact pile drivers	108,560J	6.2	5.4	4.1	3.6	75
Vibratory rollers*	Unspecified	1.3	1.2	0.9	0.8	52
Large bulldozer*	Unspecified	0.6	0.5	0.4	0.3	22
Loaded trucks*	Unspecified	0.5	0.4	0.3	0.3	19

*Suggested value for 'n' is 1.1.

Table 9. Ground vibration (peak particle velocity, mm/s) at distances of 30m from construction equipment

Vibration Threshold Criteria

Vibration threshold criteria for annoyance potential are given in Table 10.

Human Response	Maximum ppv (mm/s)	
	Transient Sources	Continuous/Frequent Intermittent Sources
Barely perceptible	1	0.25
Distinctly perceptible	6.3	1.0
Strongly perceptible	22.9	2.5
Severe	50.8	10.2

Table 10. Vibration Annoyance Potential Criteria

Source: CALTRAN 2004

DISCUSSION

BROADBAND SOUND

The overall noise determined as $L_{Aeq,1h}$ from the earthmoving operations exceeded the prescribed noise levels for restricted hours by a considerable margin and even exceeded those prescribed for standard hours. Extensive construction noise management strategies (including engineering noise controls to equipment and activity restrictions) as well as community consultation will be essential during earthmoving operations.

LOW FREQUENCY SOUND

AIRBORNE SOUND

Computer modelling of two different combinations of building element and absorptive treatment demonstrated that:

The highest noise reduction of 60 dB(A) was achieved by one combination (R5 + P5) with a high degree of internal absorption (NRC 1.02, α125 Hz 0.65) with NO window inserted in a building element having a high sound reduction of 50 dB at 125 Hz (R_W 67).

Based on the modelling it is obvious that a window design would require at least a high sound reduction value approaching that of CSR Gyprock Masonry – System No. 721 with R_W 67 and a sound reduction of 50 dB at 1/3rd octave band 125 Hz in order to achieve an internal ambient noise level of less than 45 dB(A) $L_{Aeq,2min}$ during operation of a front end loader at 30m.

For the 'weaker' combination modelled: (R1 + P1) it is possible to achieve a noise reduction of 46 dB.

It is not possible to achieve an L_{Aeq} internally of 35 dB(A) for broad band, steady noise with the front end loader operating at 30m for the superior building combination to avoid sleep disturbance as illustrated in Table 9a.

Compliance with a low frequency noise criterion L_{pALF} of 20 dB (dwelling, evening and night) or L_{pALF} of 25 dB (dwelling, day) for non-tonal noise (*LFN EcoAccess 2008*) cannot be achieved with operations of the front end loader, excavator or scraper at 30m during the day or night with building combination (R5 + P5). Building elements and window structures are required to have a far superior performance below 200 Hz to those used in the case study to satisfy low frequency noise criterion during both the evening and night periods.

The 1/3rd octave band spectrum levels at 63 Hz and 80 Hz for the grader with unsuppressed exhaust exceeded the median hearing threshold levels (HTL), f_c at these frequencies by 6 dB and 31 dB respectively. When the limit values for exceedance of the threshold values are applied (5 dB at 63 Hz and 10 dB at 80 Hz, the noise emission of the grader (unattenuated) would be rated as annoying. (*LFN 2008*)

GROUND VIBRATION

Computer modelling of the ground vibration transmitted by various items of construction equipment indicated that:

- The ground vibration decreases progressively from hard competent rock (n = 1.0) to weak or soft soils (n = 1.4).
- For hard, competent rock the ground vibration at 30m determined as peak particle velocity (ppv) varies from 6mm/s (impact pile driver, energy rating 108,560J) to 0.02mm/s (small bulldozer).

The distances required from operating heavy impact and vibratory pile drivers for continuous vibration and hard, competent rock to achieve an acceptable annoyance criteria (strongly perceptible) of 2.5mm/s at sensitive premises varies from 50m to 75m. Vibratory rollers under identical conditions require a separation distance of up to 55m. Smaller items of construction equipment under identical conditions require separation distances varying from 10m (jackhammers) to 25m (large bulldozers).

CONCLUSIONS

Disturbing construction noise can result from surface works and tunnel works during the day. For example, noise from earthmoving could be comparable to maximum noise from traffic. Surface work at night would be limited to short-term activities in particular locations.

Some people feel vibrations at much lower levels than those that cause minor damage to buildings. Construction techniques would vary according to geological conditions and the proximity of sensitive places.

Close consultation and advanced notification of approaching surface and tunnelling works for the occupants with potentially affected properties will be required. While property damage is not expected, it is generally prudent to undertake building pre-condition surveys in some areas. For heritage places, Cultural Heritage Management Plans may also be required.

Potential impacts from surface and tunnel construction and operation can be avoided or reduced by the application of good design practice but careful management is required during construction and operation of surface and tunnel projects, to maintain or enhance environmental conditions in the subject area.

The sound insulating properties of double glazed window configurations fitted into an external building element would have to be exceptional and at least have a performance equivalent to or superior to that of the masonry system selected from the CSR Gyprock Redbook (*CSR Manual*)) having a R_W of 67 and sound reduction of 35 dB at 100 Hz and 50 dB at 125 Hz.

Due to the high sound energy in the 125 Hz to 160 Hz 1/3rd octave bands prevalent in the front end loader and excavator noise spectra it is envisaged that thicknesses of laminated glass exceeding 10mm, an absorptive airspace of at least 200mm and surface mass density > 60 kg/m^2 would be required to achieve the low frequency sound transmission loss below 160 Hz .

To maximise the improvement due to an air space, the window system would have to be designed so that the 'mass-air-mass' cavity resonance was as low as possible below 80-100 Hz with the type of absorptive material used in the window reveal having a NRC of at least 0.75. Specifications of double glazed configurations sourced from various manufacturers indicate that they are unlikely to achieve this performance and a special design would be necessary based on a triple glazed window configuration. Such an option would only be considered for long term construction operations and where artificial screens close to the source/s and equipment modifications do not achieve the appropriate outcome.

The distances from operating heavy construction equipment to sensitive premises for continuous vibration and various soil types must be carefully chosen to achieve an acceptable annoyance criterion (strongly perceptible) of 2.5mm/s. These distances can vary from 20m to 75m depending on the mechanical or energy rating.

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