Traffic-induced building vibration – A tool for planning of land use

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Summary

This presentation describes simplified design advice for assessment of traffic-induced vibrations in land use. The guidelines include a vibration criterion, limit values, vibration measurements and evaluation of building vibrations. The proposed vibration criterion for building vibration is related to the frequency-weighted rms value. The vibration measure is the statistical maximum measured during one week. The proposed assessment of building vibrations is based on triaxial ground vibrations measured on the building site. In addition to magnitude, the frequency spectrum of vibrations is also used in predicting building vibrations. The vibration design is based on two approaches; one considers the uniform magnification of the vibration and the other the magnification in the resonance. The resonance design shows which floor spans and building heights should be avoided.

Keywords: traffic, vibration, traffic-induced vibration, land use, limit value, vibration design, magnification, resonance, frame, floor

1. Introduction

Traffic-induced building vibration may cause unacceptable nuisance for people living close to roads or railways. Often the vibration originates from heavy traffic and disturbs residents mostly at night. Due to the shortage of building land and the current need to reduce traffic-induced air pollution, there is growing pressure to build new dwellings close to traffic lanes and move transit traffic to tunnels. At the same time, rising standards of living set higher quality requirements for the living environment. Vibrations may restrict the use of land close to traffic routes. The Finnish Building Code and many other building regulations provide that vibration shall not cause damage to a building or excessive disturbance to its occupants. There is a strong need to develop and harmonise methods, tools, procedures and knowledge for traffic vibration to a similar level as has been achieved for noise during the last two decades. Especially the designers participating in the planning of land use need unified models and tools for dealing with vibration.

Traffic-induced ground vibration can be harmful due to building vibration or structure-borne noise. Which of these dominates depends on the frequency content of ground vibrations. Low-frequency building vibrations are typical in soft soils while audio frequencies are typical in hard soils. This presentation focuses on building vibrations of 1–80 Hz and is therefore not applicable to structure-borne noise (16–500 Hz).

It is typical of transit traffic in Finland that the roads and railways are situated on flat clay areas that are often surrounded by rocky hills (Fig. 1). More and more of these areas, which are especially sensitive to ground vibrations, are being put to effective use. Low-frequency vibrations, usually in the range of 4–10 Hz, spread effectively in clayey soils and are difficult to estimate. Often the horizontal component of the vibrations is higher than the vertical component, and frequencies with a very narrow band dominate.

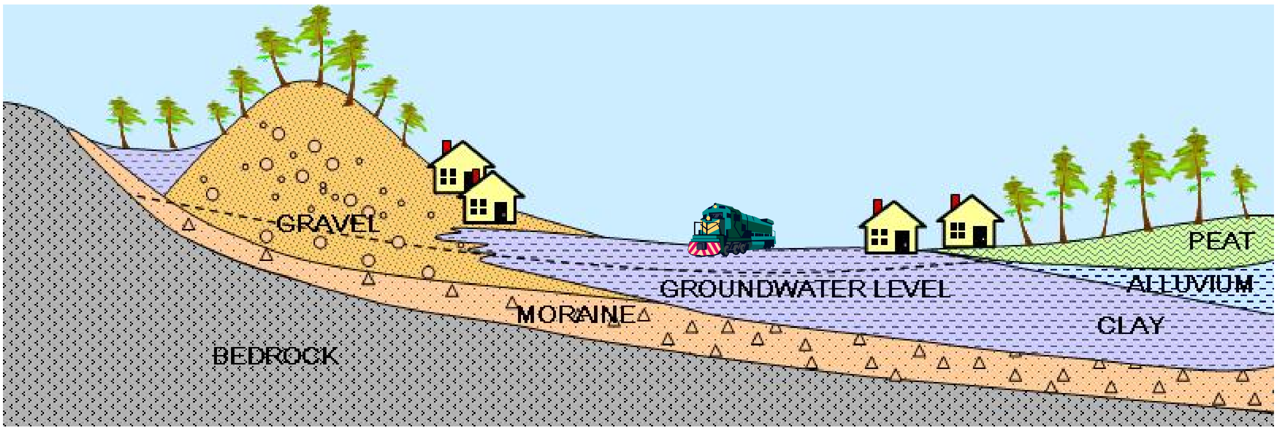

Fig. 1 Typical soil conditions in Finnish coastal areas

The proposed assessment of traffic-induced building vibrations is based on measured vibrations in ground and buildings, on numerical FE calculations and on a literature study [1]. Altogether 36 buildings were measured. Seven of them are high-rises with at least three storeys and the other 29 are one- or two-storey low-rise houses. All the high-rise buildings are from clay areas. Seven of the low-rise buildings are from sand or gravel areas and the remainder are from clay areas. The vibration is induced by railway traffic in 22 houses and by street traffic in 14 houses. FE analysis of the frame was based on a simple two- to three-storey plane model and the examination of the floor on a simply supported beam model. The FE study is based both on the statistical resonance study and on the measured vibration signals.

2. Vibration criterion

The disturbance in the residences may be caused mainly by horizontal movements of the building frame or by vertical movements of the floors (Fig. 2). Therefore the vibration criterion is based on the maximum vibration component measured trixially in three orthogonal directions.

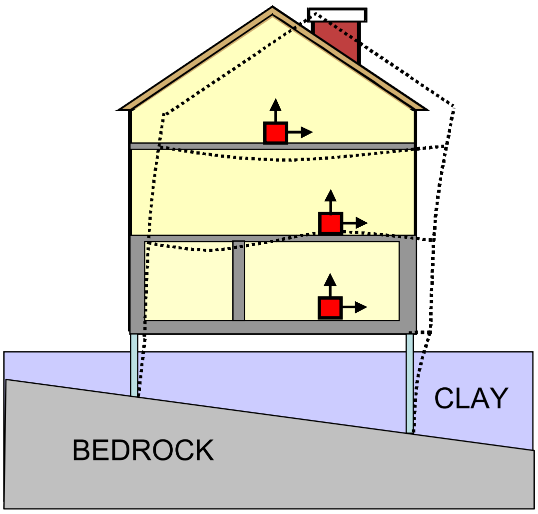

Fig. 2 Scheme of building vibrations and vibration measurement points

Table 1 Basic vibration concepts

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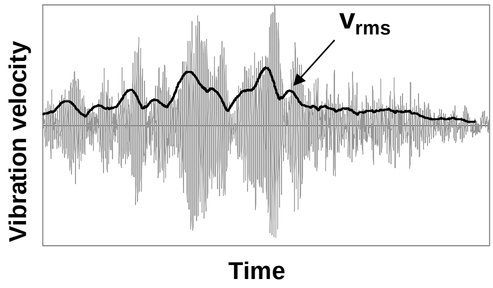

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Rms velocity of vibration v_{rms} [mm/s]

Rms velocity of the signal v(t) at the moment t_0 is

$$v_{rms}(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} [v(t)]^2 \mathrm{d}t \right\}^{\frac{1}{2}},$$

where the time window τ is 1 second.

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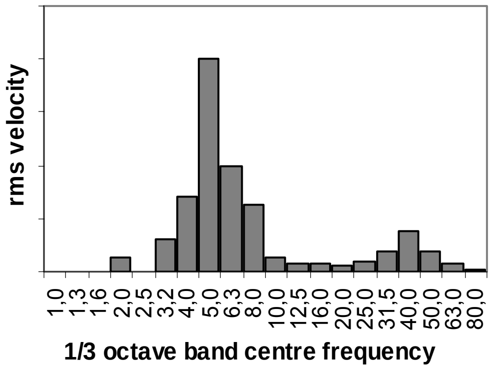

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Vibration spectrum

The vibration spectrum shows the vibration components of the signal in 1/3 octave bands. When the spectrum is based on time window τ =1 s, the rms velocity may be presented in the frequency domain by

$$v_{rms}(t_0) = \sqrt{\sum v_i^2}$$

1/3 octave bands: centre frequencies f_c and upper cut-off f_2 of bands 1…80 Hz

$$f_c = 10^{n/10},\ n = 0...19$$

$$f_2 = 10^{(n+0,5)/10},\ n = 0...19$$

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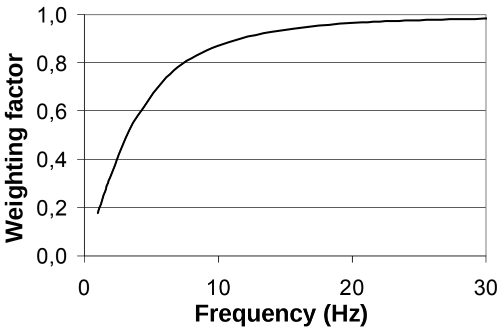

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Weighting factor for vibration spectrum

The weighting factor makes different frequency components of the vibration spectrum equivalent to human sensitivity. The figure shows the weighting for vibration velocity.

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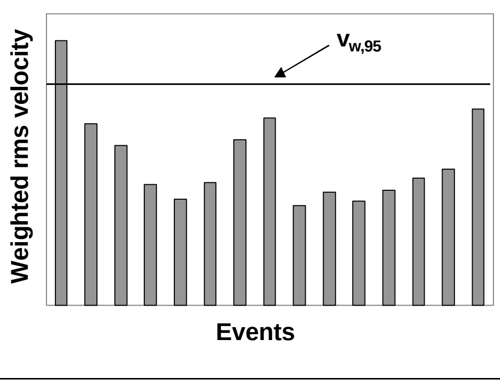

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Vibration level $v_{w,95}$ [mm/s]

The vibration level $v_{w,95}$ is the statistical maximum of vibration measures v_w, based on the 15 events which generate the maximum vibrations during one week. If necessary, the vehicles may be grouped in different categories. The vibration measurements should represent the normal state of track and traffic.

$$v_{w,95} = \bar{v}_w + 1.8 \cdot \sigma$$

where $\bar{v}_w$ is the mean value and σ is the standard deviation of the measuring results.

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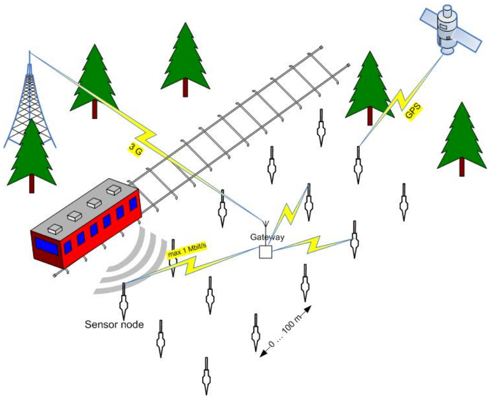
The basic vibration concepts are shown in Table 1. The vibration measure v_w is the momentary maximum of the frequency-weighted rms velocity of one event (NS 8176 [2]). The vibration can also be measured as frequency-weighted acceleration a_w. Then weighting W_m of ISO 2631-2 [3] is used. The transformations between velocity v_w [mm/s] and acceleration a_w [mm/s^2] are given by $v_w = a_w/35.7$ [2]. The vibration level $v_{w,95}$ is determined as a statistical maximum rms velocity measured from events over one week. In practice the vibration level is determined from 15 one-second samples, which generate the maximum vibrations, as shown in Table 1.

The vibration limit $v_{w0} = v_{w,95} = 0.6$ mm/s is proposed for buildings in existing residential areas and $v_{w0} = 0.3$ mm/s for those in new residential areas. These values have originally been proposed by NS 8176 [2] and they are in line with many other guidelines. For example, values of 0.2–0.3 mm/s [4], 0.4 mm/s [5] and 0.25 mm/s [6] have been presented for new areas, and values of 0.6 mm/s [4] and 1.0 mm/s [5] for existing areas.

3. Measurement of ground vibrations

The proposed assessment of traffic-induced building vibrations is based on triaxial ground vibrations measured from the building site. Modern technologies – wireless measuring and geographic information systems together with web applications – offer an effective platform for measuring vibrations, monitoring the events and visualisation of the results (Fig. 3).



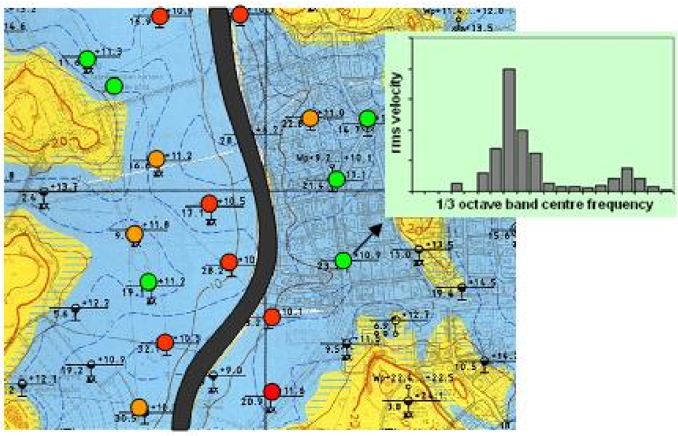


Fig. 3 Scheme for wireless, remote-controlled vibration measuring network, and visualisation of measured vibrations on a geological map

The starting point for the vibration assessment is the vibration level $v_{w,95}$ and average vibration spectrum measured from the ground (Fig. 4). The average spectrum is determined from the same 15 one-second samples that are used in the determination of vibration level $v_{w,95}$. The average spectrum is calculated as the product of the vibration level $v_{w,95}$ and the normalised vibration spectrum, which is determined from the measured vibration spectra: First each spectrum is normalised by dividing the frequency components by its rms vibration, then the normalised vibration spectrum is determined by averaging them.

4. Vibration assessment in decision-making

The size of the building and the spans of floors may have a great influence on the vibrations perceived in dwellings. The building vibrations are estimated by two approaches: one considers the uniform magnification of the vibration and the other the effect of the resonance. The steps in the assessment of building vibrations are shown in Fig. 5.

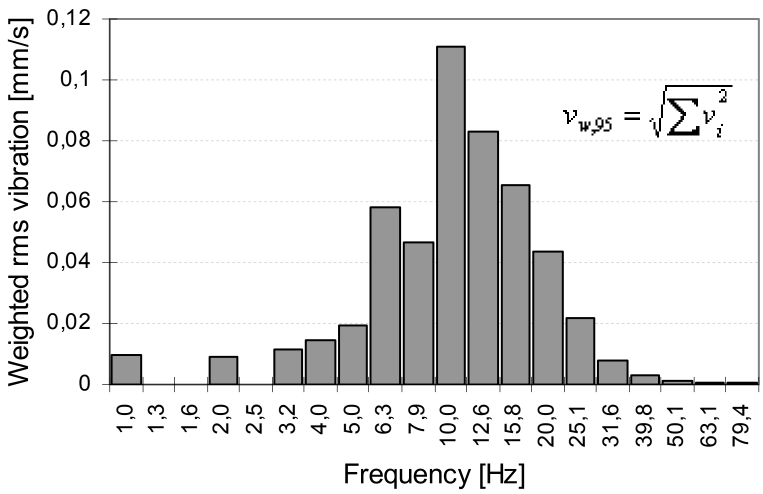


Fig. 4 An example of a ground vibration spectrum which corresponds to vibration level $v_{w,95}$=0.18 mm/s

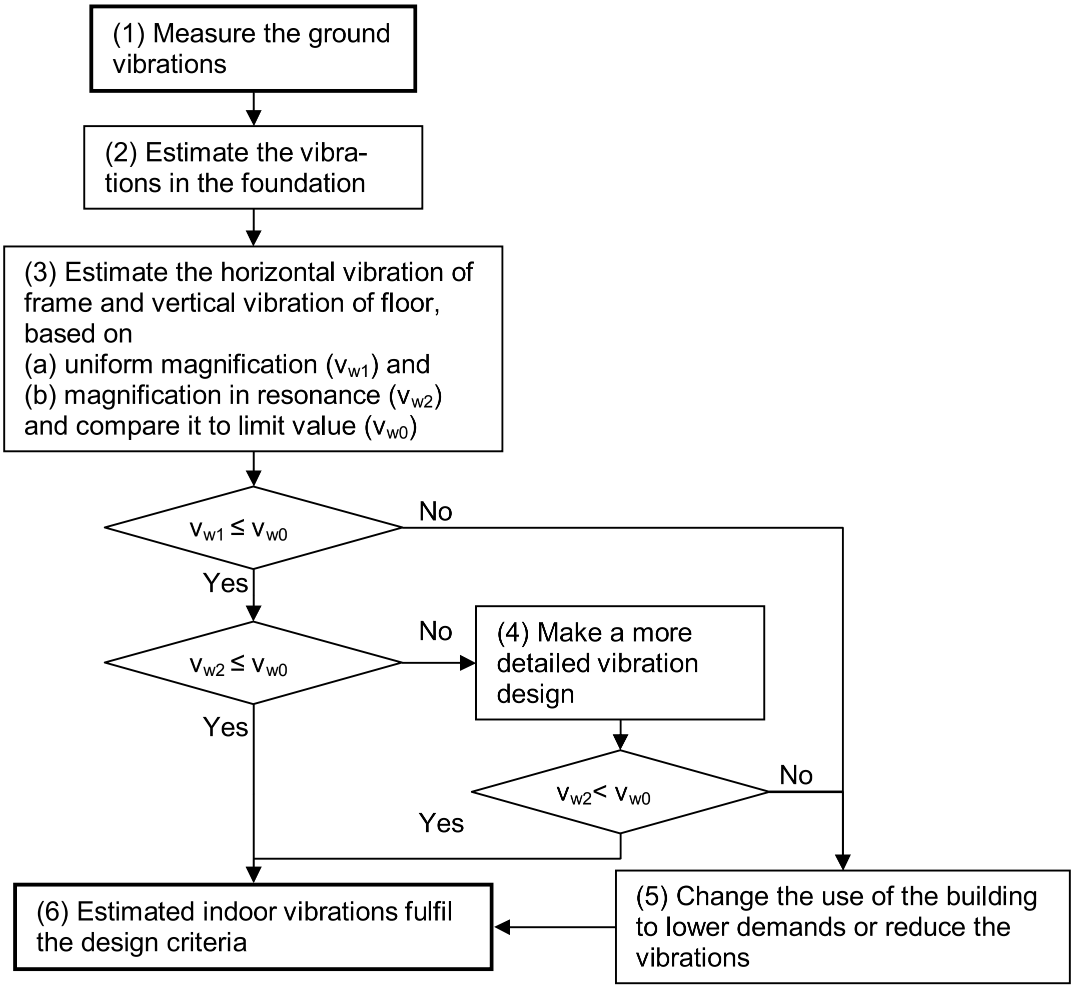


Fig. 5 Steps in assessment of building vibrations

The estimate for the vibration spectrum of the foundation (step 2 in Fig. 5) is determined by multiplying the vibration spectra of the ground by reduction factor

$$k_i^{found} = -\frac{A}{\lg 8} \cdot \lg\left(\frac{f_i}{80}\right) \text{ , but } k_i^{found} \le A \tag{1}$$

where f_i is the centre frequency of the considered 1/3 octave band. Some guidelines (e.g. [6]), propose values of A<1.0 for multi-storey buildings. However, if better experience is not available, the same value of A = 1.0 is proposed to be used in all cases for both horizontal (directions x and y) and vertical (direction z) vibrations. Equation (1) is shown graphically in Figure 6.

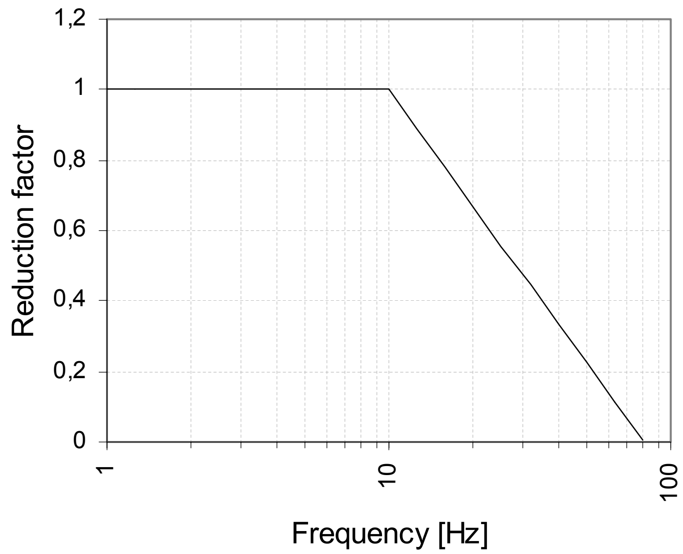


Fig. 6 Graphical presentation of Equation (1)

The estimate of the vibration levels of the foundation (directions x, y, z) is determined from

$$v_{w,95}^{found} = \sqrt{\sum_i \left(v_{w,i}^{found}\right)^2} \text{ , where } v_{w,i}^{found} = k_i^{found} \cdot v_{w,i}^{ground} \tag{2}$$

The estimate of vibration v_{w1}, based on uniform magnification in the building (step 3a), is determined from

$$v_{w1} = k_1 \cdot \max(v_{w,95}^{found,x}, v_{w,95}^{found,y}, v_{w,95}^{found,z}) \tag{3}$$

where $v_{w,95}^{found}$ is the vibration level of the foundation in directions x, y and z. Factor of k_1 =1.5 is recommended for normal design. However, if the base floor is in direct contact with the ground in all directions, as in the case of a one-storey house with a ground-supported base floor, a lower value of k_1 =1.0 is proposed. If the vibration level v_{w1} is more than the limit value v_{w0}, vibrations should be reduced or the use of the building should be changed (step 5).

The vibration v_{w2}, based on resonance, is estimated by magnifying all 1/3 octave bands (step 4b) according to

$$v_{w2} = k_2 \cdot \max(v_{w,i}^{found}) . \tag{4}$$

For floors, $\max(v_{w,i}^{found})$ is the greatest vertical (z direction) component in the vibration spectrum of the foundation, and a factor of k_2 = 6.0 is recommended. For frame, $\max(v_{w,i}^{found})$ is the greatest horizontal component (directions x and y) of the foundation, and a magnification value of k_2 = 4.0 is recommended. A more detailed vibration design (step 4) is necessary if either of these vibration levels v_{w2} is more than the limit value v_{w0}.

In more detailed vibration design (step 4) the number of storeys and the span of floors are fixed so that the fundamental natural frequency of the floor does not fall in the dominating frequency bands. In the example shown in Fig. 7, the resonance vibration v_{w2} is less than the design limit v_{w0} = 0.3 mm/s, if the natural frequency does not fall in the 1/3 octave bands 10.0 Hz or 12.6 Hz. According to the usual fundamental natural frequencies for building frames and according to the calculated natural frequencies of the example floors shown in Fig. 7, the condition for natural frequency is not fulfilled if the building is a two-storey house or the span of the selected floor type (floor 3) is 6.7–8.4 m

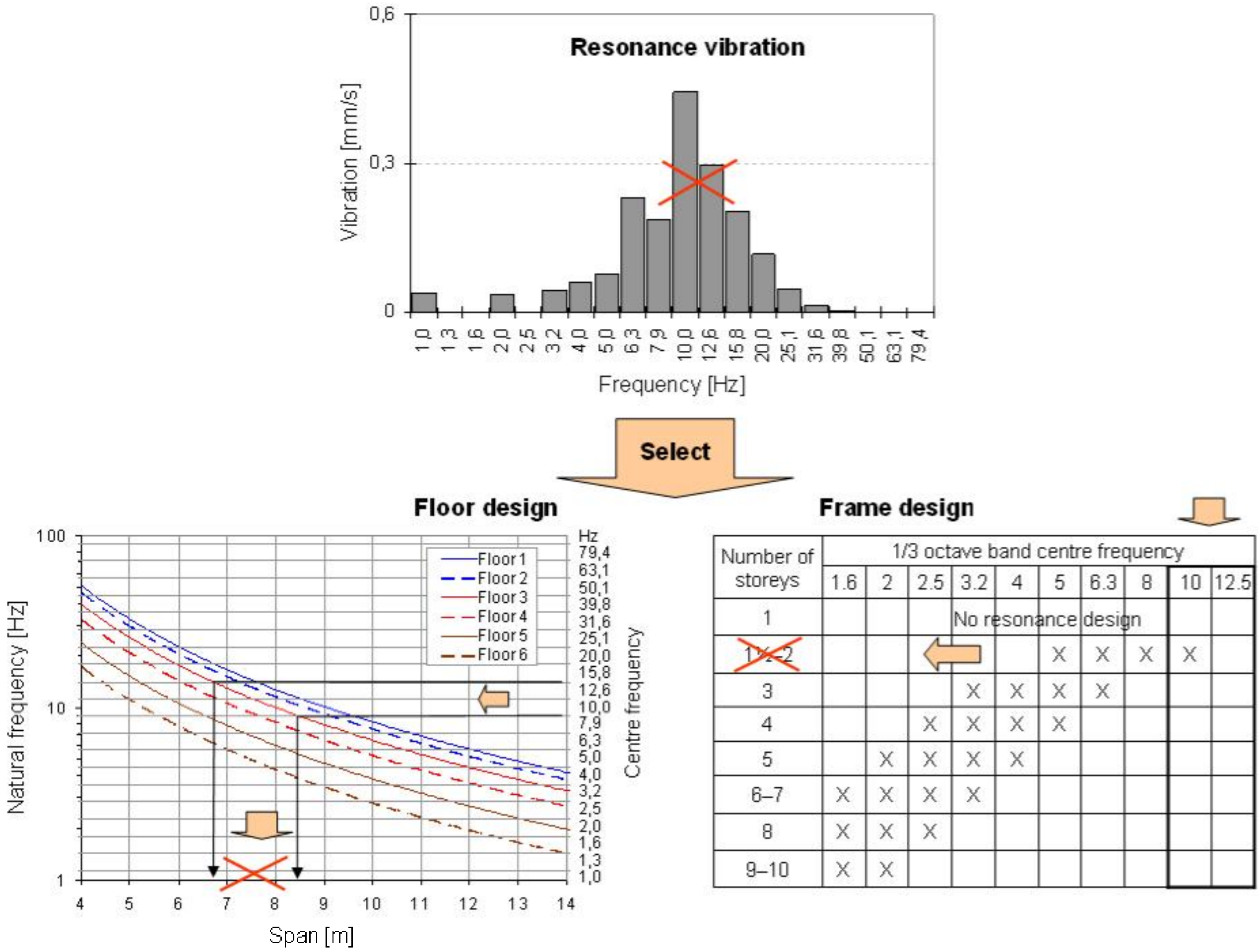


Fig. 7 Scheme for selecting floor and frame dimensions so that the resonance vibration is not determining

Often the use of very low natural frequencies of floors is limited by other design conditions (deflection, strength, walking-induced vibration, etc.). Then it is enough to know the lower limit of fundamental frequency f_0. For single-span floors it can be approximated by equation

$$f_0 = \frac{\pi}{2 \cdot l^2} \sqrt{\frac{(EI)_l}{m}} \qquad (5)$$

where l is the floor span, $(EI)_l$ is the floor bending stiffness per unit width, and m is the floor mass density per unit area (increased by a service load of 30 kg/m^2). The equation is valid also for multispan floors with equal spans. If the spans are different, the frequency based on the largest span *l* gives a lower limit approximation. In addition, high transverse stiffness of the floor, together with supported longitudinal edges, raises the frequency.

The accurate calculation of the fundamental frequency of a building frame is very complicated. Therefore usually it has to be assumed that the frequency can fall in any of the 1/3 octave bands shown in Fig. 7 (ISO 4866 [7]). If necessary, more detailed information for standardised houses can be obtained by vibration testing. In the case of single-storey houses, the resonance design is not necessary, because the frame vibration has no influence on vibrations of the base floor.

If the proposed design approach does not give acceptable results, vibrations should be reduced, or the use of the building should be altered (step 5). As the methods for mitigating vibrations afterwards are limited and costly, the risk should not be taken in any case if the estimated vibration level exceeds 0.6 mm/s, which is the proposed limit for existing dwellings. The principles of vibration mitigation are shown in Fig. 8: (a) traffic limitations and improved track condition, (b) vibration isolation of track, (c) track support on hard soil, (d) vibration barrier, (e) building support on hard soil, (f) vibration isolation of the building, and (g) structural design. However, the true reduction depends greatly on the shape of the vibration spectrum and on vibration direction, e.g. the piling of the building can even magnify the horizontal vibrations (see Fig. 2). Also, the usual vibration isolation systems under the track or building, which are mainly used for mitigation of ground-borne noise, work poorly in soft soils. In any case, much more experience of mitigation methods for vibrations of 4–10 Hz in soft soils is required.

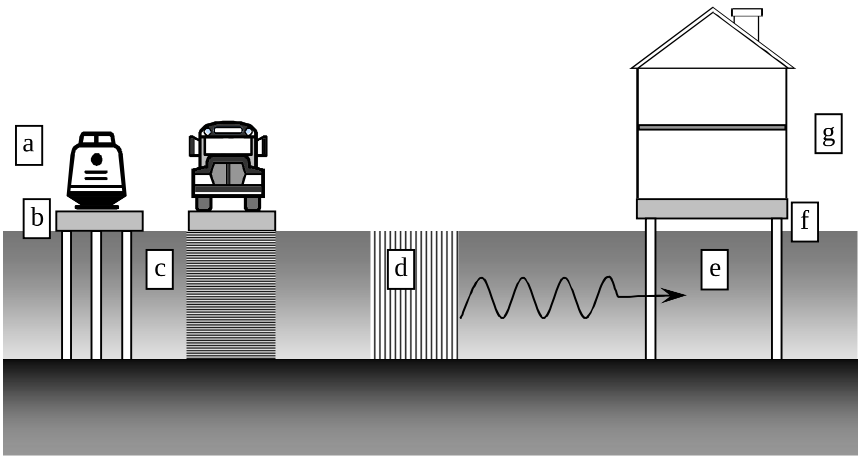


Fig. 8 Scheme for mitigation of ground-borne vibration in different points of the vibration propagation path

5. Discussion

This presentation describes a simplified design tool for vibration assessment. The approach is proposed as a means of unifying inconsistent practises and to serve as a platform for the further development of vibration assessment. In addition to the vibration level of ground vibrations, the direction of vibration and frequency spectrum must be known; otherwise the basis for vibration design is inadequate. The proposed method for building vibration assessment is meant to provide an approximate estimate for the preliminary design phase. If necessary, it can be adjusted by performing a more detailed vibration study.

The proposed assessment is based on ground vibration, which is measured triaxially on the building site. It is proposed that the characteristic information on vibration in each direction is given by a statistical maximum rms vibration level and by an average vibration 1/3 octave spectrum. The 1/3 octave band approach is already proposed in some guidance [6] and it is consistent with conventional noise assessment. The unified presentation of results means that the measuring reports are comparable and the further utilisation of results is more straightforward. If e.g. the effect of vibration mitigation is known band-specifically, then its effect on the total vibration level is easy to calculate.

The new method proposed for vibration design considers overall magnification and resonance case separately. Therefore it is possible to design the fundamental frequencies of the building frame and the floor so that they do not coincide with the dominating frequencies of ground vibration. The approach makes it possible to design the height of the building and the spans of floors so that resonance does not magnify the vibrations. In resonance design only that 1/3 octave band in which the fundamental natural frequency of structure falls is magnified. For this 1/3 octave band, a high amplification factor of 4–6 is used. For overall magnification the factor is only 1.0–1.5. If the resonance design is not considered as a case of its own, higher factors for overall amplification should be used: Nordtest [8] gives an indicative factor of 4.0 for the frame and floors of a two-storey house. Based on statistical results given by Madshus et al. [9] the design factor should be about 3–4 for the floors and 4–5 for two-storey frames. Measurements made by Hunaidi and Tremblay [10] show amplification factors of about 3.0. According to Nelson and Saurenman [11] the typical amplification for floors is 1.8–5.6. Investigations in Japan [12] show typical amplifications of 2-5.

There are many future research needs. Today there are many areas where traffic vibrations are too high for residential buildings. Traffic-induced ground-borne vibration, especially in soft layered soils, is a far more unknown and more complex phenomenon than e.g. airborne noise. Because no sufficiently reliable method for predicting ground vibrations is available at present, more effective measuring tools are necessary. The designers participating in the planning of land use also need effective tools for decision making, so that the problems can be solved in the early design phase of land use. However, at least in Finland, the most urgent need is to find the best methods for reducing the vibrations of soft soils. The low frequencies of 4–10 Hz are much more difficult to isolate than the audio frequencies of hard soils. Mitigating vibrations afterwards is difficult and expensive.

6. Acknowledgements

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