

ASSESSING NOISE AND VIBRATION IN BUILDINGS USING FINITE ELEMENT MODELLING: UNDERSTANDING THE FACTORS INFLUENCING PREDICTIONS

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1 INTRODUCTION

For many new buildings, there will generally be a good 3D CAD model of the geometry of the structure provided by the architects or structural engineers of the project. The geometry model itself may therefore be used to build a Finite Element (FE) model of the structure in order to predict vibration or noise due to various sources of excitation. However, there are many factors that can have a strong influence on the predicted levels: the material properties of the modelled structural elements such as the dynamic Young's modulus of elasticity, the level of assumed damping, additional furnishings and fittings superimposing onto the main structure, constraints associated with the foundations or perimeter wall in the form of piles, soil-structure interaction, and last but not least, the location of response points. Additionally, it is almost impossible to design a new building by considering all dynamic loading eventualities; unlike the static loading, the vibrational energy into a building would often vary throughout most parts of the day, as in the case of railway lines, and as such it is difficult to have a fix on a precise level. This paper will present two case studies dealing with the assessment of noise and vibration in buildings using the FE modelling method. The first case study presents the methodology of predicting vibration in a new state-of-the-art science building due to footfall and road traffic excitation. The parameter variation of some factors, such as the dynamic Young's modulus of elasticity and location of response points, is discussed as a means of illustrating how the predicted outcome may be affected. The second case study focuses on the methodology of predicting noise in multi-storey buildings above underground railway lines and also discusses some key factors that can have an influence on the predicted noise levels.

2 VIBRATION PREDICTIONS FOR SENSITIVE BUILDINGS

2.1 Methodology and Modelling Considerations

The process of constructing FE models of buildings is firstly based on either imported CAD geometry or on a fairly laborious manual process whereby hardcopy drawings may be used to develop an FE model from the ground up. The main features of the modelling process require the following considerations:

- Most structural elements would normally be modelled as plate elements (rather than solids to reduce computational time when using an FE software package). This would involve all floor levels of the building (both basement and superstructure where applicable), internal walls and lift shafts. Also, structural columns between floors levels would need to be modelled as beams with representative cross-sectional properties at their exact location.
- Piles buried into the underlying strata would at least be modelled with an equivalent spring stiffness, including torsional stiffness considerations. Additionally, most new buildings have a secant pile wall as part of their footprint. Given that there is an overlap between these thick piles, a perimeter wall of equivalent thickness may be modelled instead.
- The ground/substrata stiffness would be modelled with spring elements under the modelled slab foundation in the presence of data provided by an appropriate geotechnical survey.
- A level of 'non-structural' mass, i.e. mass with no stiffness, should be added to each floor level of the modelled building based on the static loading of the partitions, furnishings and any false floors, including a representative percentage of dynamic live load.
- Movement joints should be modelled, where appropriate, since they would normally isolate vibration sensitive areas from plant room areas.

- The dynamic Young's modulus of elasticity of concrete should be appropriately chosen. There are specific values that can be used for concrete, but it is difficult to ascertain a fixed value for the complete lifetime span of the building. This is because 'cracking' of concrete may for instance occur due to temperature gradients between the surface and core of a concrete slab, which is likely to be more evident in thicker slab constructions. Cracks in concrete may form in highly non-linear manner and is not possible to predict. The effect of cracking in concrete will likely weaken the slab, and as a result, a much lower value of dynamic Young's modulus of elasticity should probably be used as a conservative estimate when dealing with cracked concrete slabs. However, there is no fixed rule for this. Additionally, it has been shown that the curing process of concrete is important. In particular, it has been shown that concrete allowed to dry-cure, i.e. exposed continuously in air, could only achieve the 40% compressive strength of a 180-day wet-cured concrete¹. Therefore, the length of time during which the poured concrete is kept moist can directly affect the resulting strength and Young's modulus of elasticity of a slab, due to the different extent of the early age drying shrinkage and resulting cracking within the mass of the structure.
- In the case of assessing the effect of vibration from external sources onto the building, it is important to understand how the excitation energy will couple with the underlying strata before ultimately entering the modelled structure. For instance, in the case of underground railway vibration, the energy will radiate through the tunnel invert, into the multi-layer ground and up into the building through the piled (or non-piled) foundation. Also, the soil-building coupling loss factors may vary depending on design of the building. Empirical correction factors may not be so accurate for buildings with more unusual layout and foundations, e.g. a building with multiple basement levels and no piles.
- The level of structural damping in the building would be selected and likely vary depending on how heavily furnished, or not, each floor level is. The chosen value of damping may have a profound effect on the predicted vibration responses especially when the response point is close to a resonance of the floor or wall structure.
- The location of excitation and response points in a building is important. It is possible to map out the vibration response on a complete floor level due to a single point force, but it is rather likely that there would be multiple excitation points as there would be response points. For instance, plant, such air handling units, pumps and compressors may spread across the various floor levels of the building and as a result the dynamic loading conditions of the model could be multiple.
- The temporal and frequency response characteristics of sources of excitation may widely vary throughout the day. Some sources may be constant, impulsive or intermittent in nature and the resulting input spectral energy to the model may be either broadband or tonal in character. In other instances, the energy may be concentrated in specific frequency bands. In terms of the various sources of excitation, the following internal and external sources of vibration may be considered in an FE model: a) road and railway traffic in the near or far vicinity of the building, where appropriate, b) footfall excitation from people walking in lab areas, corridors, offices and staircases, c) vibration from MEP services in plant rooms and other floor levels of the building, d) vibration from dropping goods in loading/delivery areas, building and plant maintenance, access to interstitial floor levels by personnel and lifts, and e) induced vibration due to noise from HVAC systems in highly sensitive laboratory areas.

It is imperative to underline that detailed FE modelling of buildings is perhaps one of the most accurate method of assessing the implications of a particular design aspect of a project. However, it is also almost unfeasible to predict vibration responses for every possible eventuality. It is also likely that higher overall vibration levels would be anticipated by accounting for the cumulative energy of all vibration sources when operating simultaneously within a building. Furthermore, the model should more appropriately be seen as a design tool by which other members of the design team can gauge the likely contribution of each vibration excitation source. For example, the design team may be interested in understanding the implications of a particular set of chiller units in the vicinity of a vibration sensitive laboratory area, or might be interested in understanding the vibration response of lab or specific office spaces due to local footfall excitation.

2.2 Vibration Modelling of a Science Building

There has been a requirement to assess the impact of vibration sources on a new state-of-the-art science building. The proposed scheme is to house highly sensitive equipment on two separate underground floor levels dedicated to experimental work involving the use of lasers, super-cooled magnets and various analytical instruments, such as Scanning Tunneling Microscopes (STM), Atomic Force Microscopes (AFM), as well as growth processes such as Molecular Beam Epitaxy (MBE). The vibration assessment involved the development of an FE model of all laboratory areas spread over the two basement levels including the ground floor level that would house offices and other function rooms. All structural elements (floor slabs, internal walls, columns, secant pile/perimeter wall and movement joints for plant room areas) were modelled including typical static and live load information per floor level. Non-structural elements were not explicitly modelled, such as interstitial floor levels and partitions. The stiffness of the ground was also included in the model based on a separate geotechnical survey through the use of appropriate spring elements in the FE model. Figure 1 shows the model without the structural perimeter (secant pile) wall of the building using Altair's HyperMesh FE software package with a manageable size of 60,000 nodes in total. Results were predicted up to 100 Hz:

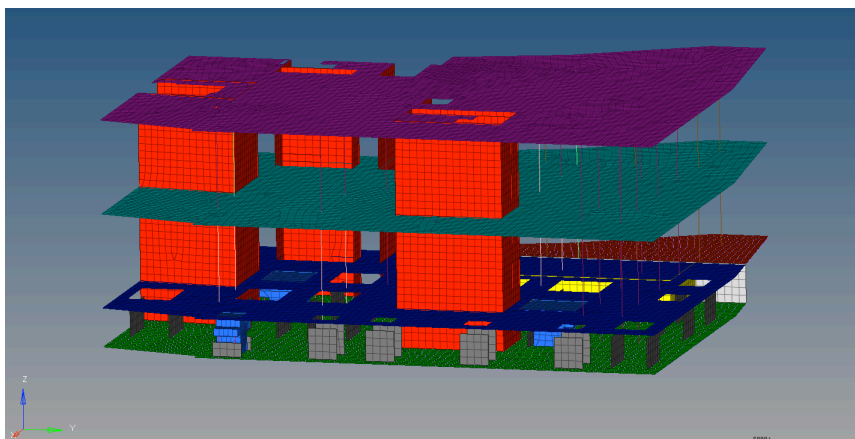


Figure 1: FE model of a science building

2.2.1 Forced Response Predictions

The FE model was excited using a variety of sources as mentioned in section 2.1. However, this paper indicatively concentrates on the effect of footfall and road traffic on representative sensitive lab areas. The effect of varying a number of parameters, such as damping, dynamic Young's modulus of elasticity and coupling loss factors due to soil-structure interaction, on the predicted outcome is discussed. The vibration levels are compared against the industry-standard Vibration Criteria (VC) curves which are appropriate for vibration sensitive environments and are nominally applicable up to 100 Hz^{2 and 3}.

Firstly, there would be low-frequency harmonic footfall excitation from people walking in labs, corridors and staircases during sensitive experiments. The method of excitation used to assess footfall excitation is based on P345 SCI publication⁴. The assessment considers a typical footfall excitation spectrum of a single 76 kg person walking at about 2 paces per second, i.e. 2 Hz (fundamental frequency), followed by three harmonically related frequencies (4 Hz, 6 Hz and 8 Hz). The guidance document does not account for energy at higher harmonics, but an additional 4th harmonic at 10 Hz was assumed since it is likely that energy may well be present at higher frequencies; the magnitude of which can be appropriately extrapolated. Vibration predictions are then carried out on two separate locations of each lab when a single person excites the concrete floor slab at a third location.

Figure 2 shows the predicted vibration responses on the two separate locations of the lab by assuming a high dynamic Young's modulus of elasticity for concrete ($E=38$ GPa), as per the SCI recommendations³, and a high value of critical damping ($\zeta=4.5\%$) since the vibration modes of the building will be perpendicularly intercepted by heavy partitions in the labs. For comparison, Figure 3 shows the predicted harmonic response on the same locations of the lab, but using a more conservative value of Young's modulus of elasticity for concrete ($E=20$ GPa) due to the thick (over 500 mm) floor slab which is likely to be more prone to cracking, and a lower value of critical damping for fully fitted floors ($\zeta=3\%$). Note that all predicted velocity levels in Figure 3 and 4 are presented in linear steps of 10 (or equivalent to 20 dB) and plotted against the VC criteria in the relevant frequency range:

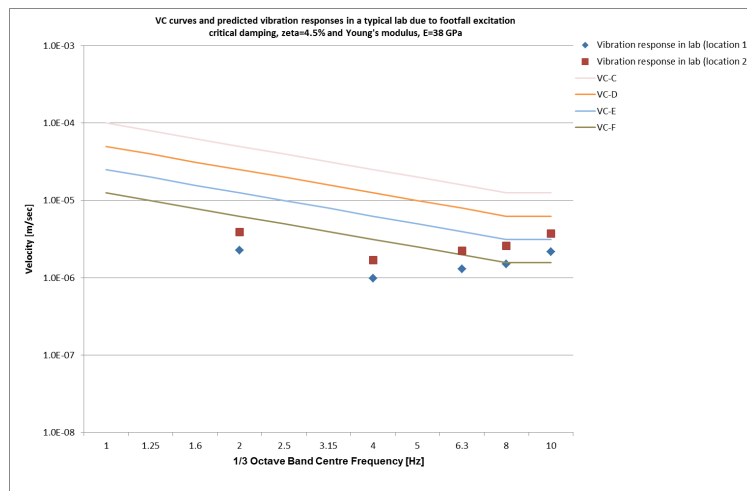


Figure 2: vibration response in a typical lab due to footfall excitation. Material properties of concrete: critical damping, $\zeta=4.5\%$ and Young's modulus $E=38$ GPa

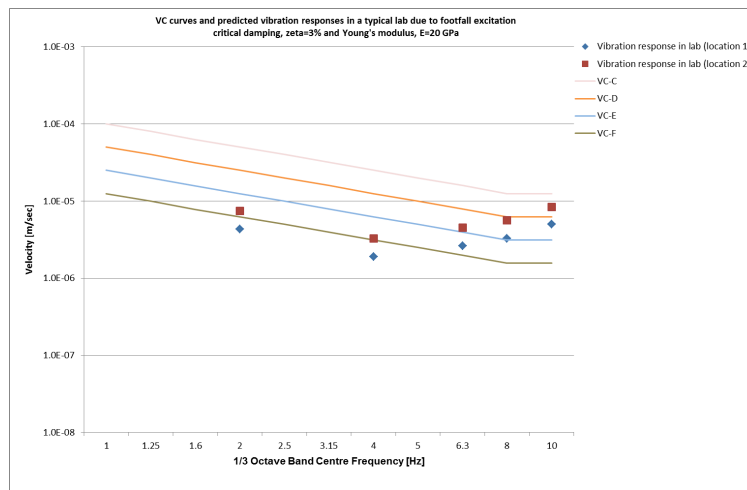


Figure 3: vibration response in a typical lab due to footfall excitation. Material properties of concrete: critical damping, $\zeta=3\%$ and Young's modulus $E=20$ GPa

The following can be deduced from Figures 2 and 3:

- The level of assumed damping and dynamic Young's modulus of elasticity will have a significant effect on the predicted vibration levels of the two locations in the representative lab. The project criterion in this case, which was VC-D, was met when assuming a less onerous set of input parameters ($\zeta=4.5\%$ and Young's modulus $E=38$ GPa). However, there will be no compliance with VC-D, especially in the 8 Hz and 10 Hz frequency bands, if more

conservative material properties of concrete were used in the model ($\zeta=3\%$ and Young's modulus $E=20$ GPa) instead.

- The predicted vibration levels will vary depending on where the person will be walking and where vibration is predicted. A person walking in the lab will not necessarily be the worst-case scenario: it depends whether the maximum amplitude of the vibration mode manifests itself more in the corridor outside the lab or within the actual lab area. At frequencies above 8 Hz, there would be multiple higher order modes of vibration in the building and there can be considerable variation between two locations of the same lab. In a real situation, there would be multiple excitation and response points, so drawing conclusive arguments about the performance of the labs against a fixed project criterion should be limited. However, this type of assessment provides invaluable advice to the design team. In this particular case, this type of assessment has revealed the need of adding additional structural columns and reinforced concrete walls in order to stiffen up the supporting floor slab of the labs and hence reducing the vibration response; this was subject to further FE modelling work.

Secondly, the impact of road traffic vibration on the most sensitive labs areas of the building is assessed. In particular, there would be a number of labs requiring heavy concrete keel blocks 'floating' (or sitting) on pneumatic air springs with very low natural frequencies tuned at around 1 Hz. This is to achieve an exceptional level of vibration control so that the most sensitive experiments can be carried out. The project requirement for these ultra-sensitive labs was set to achieve VC-M (a factor 256 lower than VC-E), which is a highly onerous extension of the original VC curves. The additional concrete keel blocks were included in the original FE model in addition to the air springs which sat on a pair of thick support walls. In this assessment, vibration responses on a representative 50-ton concrete keel block were predicted due to excitation on a typical location of the foundation slab close to support wall base, as shown in Figure 4. The latter scenario enables us to assess the vibration transmissibility, and therefore efficiency, of the coupled dynamic system (vibration isolator with air springs-support walls-building foundation slab):

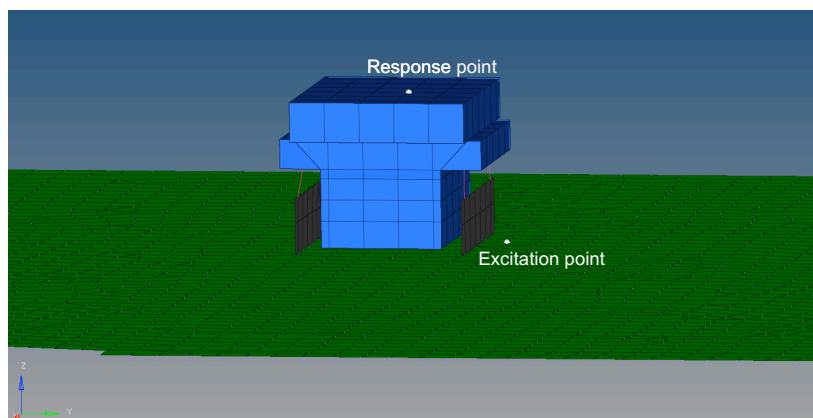


Figure 4: 50-ton concrete keel block supported by air springs mounted on support walls and foundation slab

Previous vibration measurements of road traffic in the vicinity of the new building were used to provide the energy input to the FE model and coupling loss factors between the building and the surrounding soil were also considered. Coupling losses at the interface of the building with the ground were presented about 30 years ago in the Transportation Noise Reference Book⁵ and by others. Up to 10 dB of frequency dependent vibration attenuation is recommended for a large masonry building on piles, whereas up to 15 dB of vibration attenuation is proposed for a large masonry building on spread footings. This particular science building is an embedded three-storey basement and a 15 dB of vibration attenuation was chosen for the predictions due to the anticipated high coupling loss factors of the building with the surrounding soil. Figure 5 shows predicted vibration on top of the floating concrete keel block when there is only a 5 dB (a linear factor 1.7) variation in the assumed coupling loss factor in relation to the soil-building interaction.

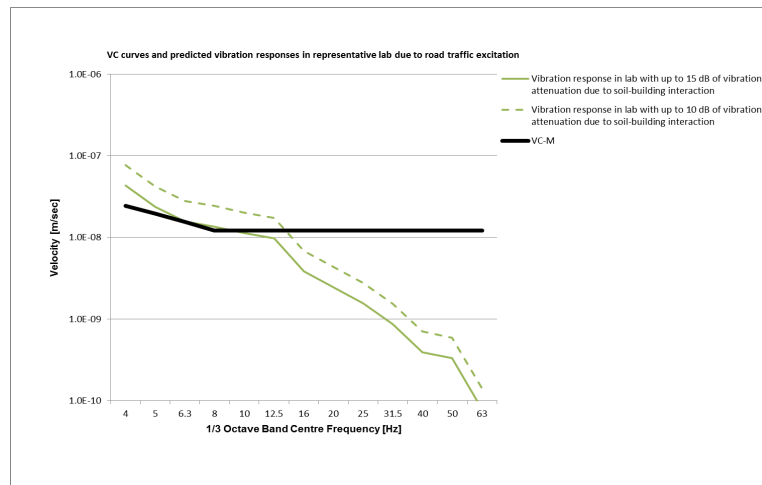


Figure 5: vibration response in a typical lab due to road traffic excitation with different soil-structure coupling loss factors

The following can be deduced from Figure 5:

- Relatively small variations in coupling loss factor values, i.e. as small as 5 dB, may affect the predicted outcome of highly critical vibration environments. In this case, VC-M can only be achieved by assuming the highest coupling loss factor (15 dB) between the soil and building for frequencies above 5 Hz. Also, there is no additional data to make a more informed decision on whether this type of structure may introduce more, or less, than 15 dB of attenuation when directly coupled with the soil. This should be the subject of further numerical modelling.
- The effect of secant pile (perimeter) wall may reduce further the vibration excitation, and hence the response on these highly sensitive lab areas may have been over-predicted. All in all, the ground should be modelled and coupled with the building and secant pile wall, adding further complexities in how the vibration excitation mechanism couples with the building.

3 NOISE AND VIBRATION PREDICTIONS FOR MULTI-STOREY BUILDINGS

Where there are concerns about vibration or structure-borne noise, multi-storey buildings can be modelled using FE techniques in order to predict the likely vibration and re-radiated noise levels.

When modelling large multi-storey buildings, simplification of the model geometry is usually necessary in order to reduce the computational resources required to solve the problem. For example, piles might not be modelled in their entirety, and structural columns might be represented as beams rather than solid elements. Where floors and walls are of relatively uniform thickness, they can often be represented by plate/shell elements. However, in these situations, care must be taken to ensure that the rotations of the different types of elements are coupled correctly, for example by specifying appropriate constraints for intersection areas where beam and plate elements are joined.

When calculating interior noise levels, the simplest approach is to assume an empirical relationship between the sound pressure level and the floor velocity level (e.g. as recommended in [5]). However, with enough computational power, the internal sound field can be calculated by including a room's internal air volume in the model. In this case, acoustic absorption is in theory included in the mechanics of the room's bounding surfaces, but in reality this rarely provides sufficient realistic damping values. Additional damping must therefore be added to the room. This cannot usually be easily accomplished at the room boundaries (due to already specifying an input velocity there), but can instead be included by specifying an acoustic loss per unit distance in the air. The precise

values are room dependent, but with some investigation can be derived from measurements and simple FE models. Additional room absorption, for example provided by large areas of soft furnishings such as beds, can be accounted for by specifying an acoustic impedance on the furniture. The total amount of damping in the room can be checked by calculating the half power bandwidth at room mode frequencies. The room damping has a notable influence on the resulting noise level, particularly at the upper frequency range (where modal density is sufficient). This can be seen in Figure 6, which has been reproduced from a recent groundborne railway noise investigation where the effective reverberation time in a small room was altered by a factor of two.

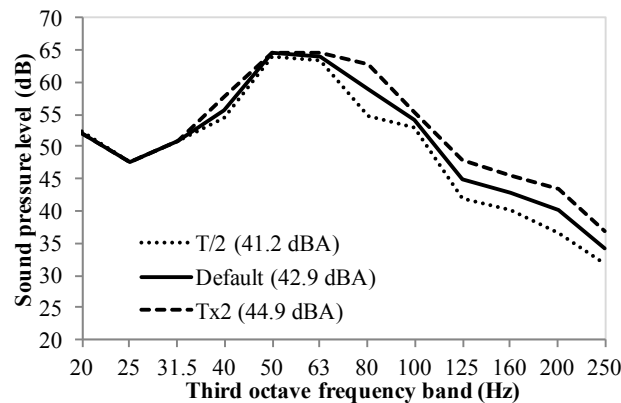


Figure 6: influence of reverberation time (T) on structure-borne noise levels in a small room

When quantifying the sound pressure level in the room, there will often be significant spatial variation due to the low frequency sound coinciding with room modes. In these conditions, it is recommended to use a low frequency evaluation technique such as that detailed in BS EN ISO 16283-1 (for sound insulation measurements in the field). In this standard, the low frequency sound is quantified by considering sound in the room corners as well as in the main room volume, with the overall value weighted between the room and corner positions:

$$L_{LF} = 10 \log \frac{2 \times 10^{\frac{L_{room}}{10}} + 10^{\frac{L_{corner}}{10}}}{3} \quad (\text{dB re } 2 \times 10^{-6} \text{ Pa}), \quad (1)$$

Where L_{LF} is the overall low frequency sound pressure level in the room; L_{room} is the logarithmic average of the sound at evaluation positions away from the room corners; and L_{corner} is the logarithmic average of the sound near the room corners.

Figure 7 has been taken from a recent prediction study of groundborne railway noise in buildings. The variation in sound pressure levels within a small room, and the benefit of using the low frequency evaluation technique is easily seen from the results.

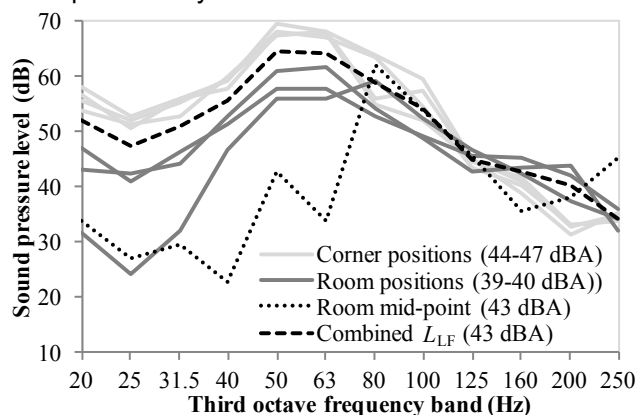


Figure 7: spatial variation in structure-borne noise levels in a small room

4 CONCLUSIONS

FE modelling of complex structures, such as buildings housing R&D facilities and multi-storey blocks of flats, can provide an informed guide to the design team for improving further the noise and vibration performance of the designed structure. However, there are many factors that can affect the accuracy of predictions ranging from the assumed material properties of structural elements through to the forcing mechanism and other modelling subtleties, such as the coupling mechanism of the foundation with the substrata, etc. It has been shown that even a relatively small magnitude variation in these parameters may affect the predicted outcome when comparing the predicted levels against onerous project criteria. Having said this, detailed FE modelling of buildings is probably one of the most accurate methods of understanding the feasibility of a particular design aspect of the project thus providing a more robust assessment framework when compared with simple analytical predictions.

5 REFERENCES

1. Curing of concrete datasheet, ARP 2006, Cement Concrete & Aggregates Australia.
2. C.G. Gordon, 'Generic vibration criteria for vibration-sensitive equipment', Proceedings of SPIE, San Jose, CA (1999).
3. H. Amick, M. Gendreau, Busch, M. and C. Gordon, 'Evolving criteria for research facilities: I – vibration', Proceedings of SPIE conference 5933: Buildings for Nanoscale Research and Beyond, San Diego (2005).
4. Design of floors for vibration: a new approach, revised edition, SCI publication P354 (2009).
5. P.M. Nelson, 'Transportation noise reference book', Butterworth & Co. (Publishers) Ltd., (1987).