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Train Induced Vibration Isolation of *theskyvue*, Sydney Australia

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ABSTRACT

Construction of a 16 level mixed use commercial and retail building known as *theskyvue* was recently completed at 413 George Street / 68 York Street in the heart of Sydney's CBD. The development straddles four active rail tunnels located only 2 m to 3 m below the site, making the proximity to the underground railway critical in terms of potential noise and vibration impacts. Extensive testing and modelling carried out very early in the design phase predicted that ground-borne noise levels could potentially exceed the project goals by up to 7 dBA on the lowest retail floor, and by 5 dBA on the most affected office floor. Mitigation of train induced vibration and associated ground-borne noise was achieved by designing and installing a complete vertical and lateral building base isolation system in the form of specially engineered laminated elastomeric bearings. Other constraints driving the design of the base isolation system related to the building's ability to withstand lateral loading from wind, out of balance earth pressures and potential earthquakes. This paper presents the detailed engineering methodology implemented to develop the specifications and to predict the performance of *theskyvue* building base isolation system. A description of the vertical and lateral isolation system is provided, together with some details on its installation. Results from compliance measurements (i) confirm that *theskyvue* development meets the ground-borne noise and vibration design goals and, (ii) validate the prediction methodology with the overall ground-borne noise levels falling within 1 dBA of the predictions.

INTRODUCTION

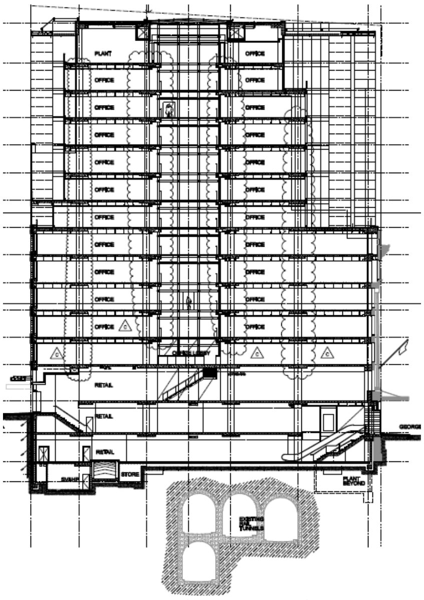
The building formerly occupied by Nock & Kirby situated at 413 George Street / 68 York Street, Sydney was demolished in 2005 to be replaced with a commercial office development with lower level retail – *theskyvue* (Figure 1). The new building constructed by Grocon consists of 16 levels including three lower levels of retail and a large atrium the full height of the office tower. The basement areas include a retail outlet, loading dock, vehicle turntable and plant room.

Technically, *theskyvue* was a challenging project due to its location 2-3 m directly above four active railway tunnels (Figure 2) - two tunnels belong to the City Circle Line and the two others to the North Shore Line. The proximity of the underground railway was a critical factor to the project in terms of the potential noise and vibration impacts associated with trains running in the four railway tunnels.

It was clearly identified that, without vibration mitigation in place, unacceptable levels of train induced ground-borne noise would occur inside *theskyvue* building. Ground-borne noise occurs when often imperceptible building vibration levels induced from the pass-by of trains cause an audible sound in the 16 Hz to 250 Hz frequency range [1]. In order to comply with the project goals established to limit the ground-borne noise levels inside *theskyvue*, a hybrid empirical-analytical detailed design model was implemented to specify the requirements for the building vibration mitigation system.

Source: (Grocon, 2009)

Figure 1. George Street facade of *theskyvue* building located at 413 George Street / 68 York Street, Sydney



Source: (Grocon, 2006)

Figure 2. Southern cross-section of *theskyvue* development. The building straddles four active rail tunnels located only 2-3 m below the site.

NOISE AND VIBRATION CRITERIA

The Acoustic Assessment [2] initially developed for the project calls for a range of rail induced noise and vibration criteria (Table 1). These are predominantly based on Australian and International Standards [3] [4] as well as guidelines from Rail Corporation New South Wales (RailCorp) [5].

The *audible ground-borne noise* design criteria almost always dictate lower vibration levels than the *tactile ground-borne vibration* design criteria. Hence, other than at facilities with particularly high sensitivity to vibration (eg scientific/medical equipment or micro-electronics manufacturing), compliance with the ground-borne noise design goals should ensure that the vibration design goals will also be achieved.

Table 1. Ground-borne noise and vibration criteria selected for *theskyvue* project

Criteria	*Indicator*	*Occupancy*	
		Retail (Level 1)	*Office (Level 4)*
Noise	$L_{Amax,Slow}$	50 dBA	45 dBA
Vibration	z-axis velocity (RMS)	-	0.4 mm/s
	Vibration Dose Value (VDV)	-	0.4 $m/s^{1.75}$

Track maintenance condition and significant variations in the rail fleet wheel condition are characteristics relevant to the management of ground-borne noise and vibration. There will probably always be a small proportion of trains with wheel defects producing higher, acoustically-significant noise events. Partly for this reason, the ground-borne noise level goals and assessment criteria advocated for this project are expressed in terms of the “5% exceedance level”, representing the loudest one in twenty train event (or 95th percentile train event).

It is useful to have such a statistically definable value as a design point, as the absolute maximum event is too undefined (ie one worst case “rogue” train at some point in the future). The intent of the “5% exceedance level” however, is clearly to address the “typical worst case, maximum noise event” for the range of train noise levels normally occurring. In the case of the Sydney fleet, the noise level of the average (median) train event would typically be 5 dBA to 10 dBA lower than the 95th percentile event. Unless otherwise specified, the noise and vibration levels presented in this paper are for the 95th percentile train event.

INITIAL TRAIN VIBRATION MEASUREMENTS

A comprehensive set of train vibration measurements was carried out at multiple locations (at the building excavation stage) on the ground surface and retaining walls, as well as inside the railway tunnels (Figure 3). Figure 3 shows the 25 m wide rail easement (railway tunnel exclusion zone) required across the site by the immediate proximity of the underground railway tunnels below. Significant transfer structures had to be subsequently designed and constructed to support the building over the rail easement.

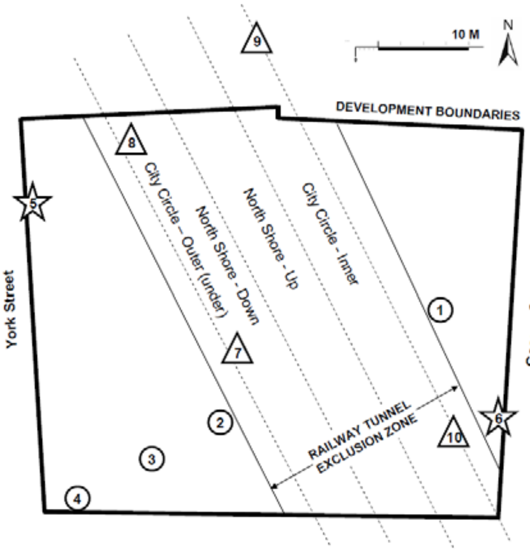


Figure 3. Site plan indicating train vibration measurement locations. Legend: ○ Surface ☆ Retaining walls △ In-tunnel

Surface Measurements

Following demolition of the former Nock & Kirby building, attended train vibration measurements were performed in September 2006 during which 55 single and 4 double train events were captured. The vibration measurements were performed on the exposed sandstone bedrock at four locations across the excavated development site (locations 1, 2, 3 and 4 of Figure 3).

The surface measurement results in Figure 4 present typical rail induced vibration spectra with peak levels measured in the 1/3 octave frequency bands 50 Hz to 100 Hz. Typically the 95th percentile train vibration levels were 10 dB higher than the average train vibration levels. This indicated a broad difference in vibration levels from train to train, and also from line to line. By removing the effect of the different lines and track conditions in each tunnel, the typical difference between the 95th percentile train vibration levels and the average train vibration levels was 5 dB.

The overall vibration levels measured at locations 1, 2 and 3 were of similar magnitude due to the proximity to the railway tunnels. The vibration levels measured at location 4 were approximately 5 dB lower than vibration levels measured at location 2; this corresponded to an approximate site attenuation of 2 dB per 10 m from the edge of the tunnel exclusion zone.

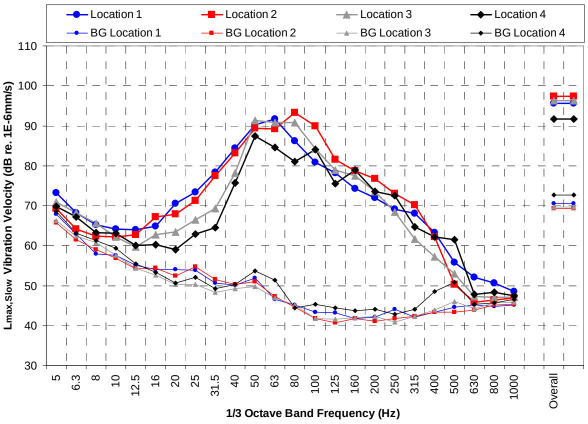


Figure 4. Vibration levels from all trains measured on the surface at locations 1, 2, 3 and 4 of Figure 3. (BG: background)

The vibration levels from trains running in the Down North Shore tunnel - and to a lesser extent from trains running in the City Outer - were significantly higher than the vibration levels from trains running in the Up North Shore and City Inner tunnels in the frequency bands between 50 Hz and 80 Hz. This suggested a significant difference in track condition between the Down North Shore line and the other two lines in the vicinity of the development site. It was suspected and subsequently confirmed during the tunnel site inspection that the Down North Shore track presented poor rail condition with significant corrugation at the time of the measurements.

Retaining Wall Measurements

Further attended train vibration measurements were performed in January 2007 on the retaining walls of the development site. A total of 61 train events were captured during the measurement period. The vibration measurements were performed in the three orthogonal directions at two locations on the retaining walls along George Street and York Street (locations 5 and 6 of Figure 3). The retailing walls at these locations are closest to the rail tunnels and represent the worst case vibration levels.

The retaining wall measurements results plotted in Figure 5 present typical rail induced vibration spectra for the 95th percentile from all train events. The vibration levels measured on the George Street wall were approximately 8 dB higher than the ones measured on the York Street wall.

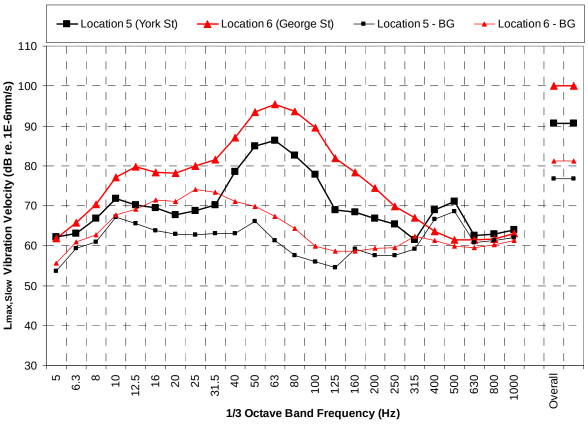


Figure 5. Vibration levels from all trains measured on the retaining walls at locations 5 and 6 of Figure 3. These represent the combined levels (logarithmic summation) in the three orthogonal directions. (BG: background)

On both walls the predominant vibration levels were measured in the vertical and longitudinal directions. It could then be concluded that the predominant transmission mechanism of train vibration into the building structure will occur vertically and normally to the retaining wall with the lateral isolation system solicited in shear and in compression, respectively.

Measurements on the retaining wall presented increased levels for trains running in the Down North Shore tunnel. This was consistent with the previous observations relating to rail corrugation.

In-tunnel Measurements

Unattended in-tunnel train vibration measurements were performed in September 2006 in the City Inner and the Down North Shore tunnels. Installation and removal of the measurement instrumentation was performed during track possession on the nights before and after the measurement period. A total of 80 single train events and 6 double train events were captured.

The vibration measurements were performed on the tunnel wall in the vertical axis at two locations in each tunnel (locations 7, 8, 9 and 10 of Figure 3). The purpose in selecting these locations was to capture the near-track source vibration levels from the trains running inside the two tunnels adjacent to the boundaries of the exclusion zone (ie the train running the closest to the foundations of the proposed building).

A comprehensive visual and photographic inspection of the tracks in the Down North Shore, Up North Shore and City Inner tunnels was conducted during the retrieval of the equipment. Due to limited time, instrumentation and access, no measurements and inspections were performed in the deeper City Outer tunnel.

All in-tunnel measurement results plotted in Figure 6 present typical rail induced vibration spectra with peak levels measured in the frequency bands 50 Hz to 100 Hz. The measured vibration levels adjacent to the near track typically contain more vibration energy in the higher frequencies above 100 Hz due to significant nearfield effects and very little ground attenuation.

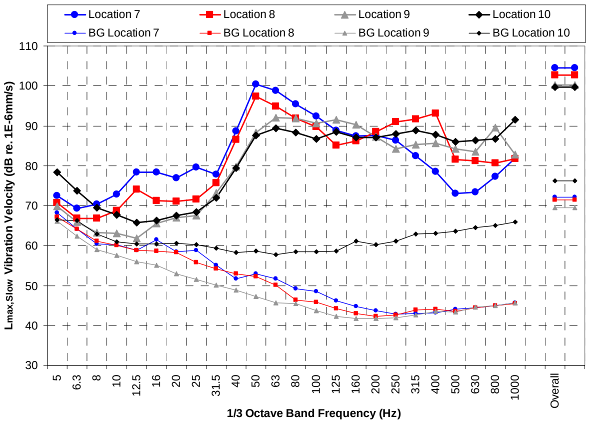


Figure 6. Vibration levels from all near-track trains measured on the tunnel walls at locations 7, 8, 9 and 10 of Figure 3. (BG: background)

The measured vibration levels from trains running in the Down North Shore tunnel presented significantly higher levels in the frequency range 50 Hz to 80 Hz. This confirmed the likely poor condition of the Down North Shore track with observed corrugation at the time of the measurements.

In general, the in-tunnel train vibration measurements correlated well with the surface measurements, with the best correlation obtained for measurements at Locations 7 and 10 inside the tunnels, as these were the locations the most in-line with the surface locations. Such correlation validated the good quality of the measured data and the adequacy of the train-induced *surface* vibration levels for predicting the ground-borne noise and vibration levels within the proposed building.

Rail corrugation was consistently observed on the Down North Shore track across the site, predominantly on the inner rail (Figure 7). Based on the rail corrugation wavelength measured at approximately 150 mm and a typical train speed of 45 km/h on this track section, the vibration frequency attributed to the observed corrugation corresponded to approximately 80 Hz.

Figure 7. Photograph of the corrugated inner rail of the Down North Shore track

Both rails of the Up North Shore track appeared smooth with a rail/wheel contact zone in a satisfactory condition. There was visual evidence of recent rail grinding on this track. No specific track features were observed along the inspected section.

No corrugation was observed on the City Inner track and the two rails appeared to be in satisfactory condition. No specific track features were observed along the inspected section.

PREDICTION METHODOLOGY

No fully-verified and generally-accepted analytical or comprehensive model exists for predicting ground-borne noise and vibration inside buildings from train-induced vibration. It is therefore necessary to rely on hybrid prediction techniques that are in part empirical. The empirical scaling is used to compensate for the different transfer functions involved in the transmission and propagation of vibration inside a building [6] [7]. Heggies has been refining his prediction methodology using a large body of measured data obtained from past projects [8].

In the case of non base-isolated buildings, the block diagram of Figure 8 specifies the hybrid model developed and used for *theskyvue* project. The input source levels used in the model are the free field train vibration levels measured on the excavated surface and the site retaining walls. In the special case of base-isolated buildings, the attenuation obtained from the vertical (and lateral) isolation system must be included as an additional transfer function in the form of an insertion loss in the prediction process.

Input Train Source Vibration Levels

In order to include all possible transmission mechanisms into the building, a unique train vibration source spectrum is obtained by logarithmically summing the vibration levels measured on the surface and on the retaining walls. The source levels are representative of the 95th percentile train from all events in all four tunnels measured at locations presenting the highest levels (worst-case scenario).

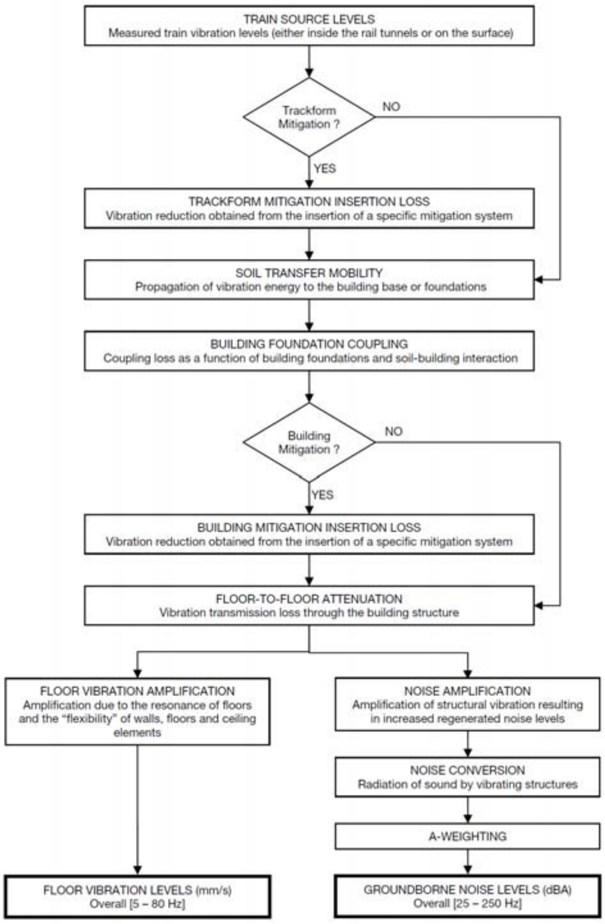


Figure 8. Block diagram of hybrid train induced noise and vibration model. All input and transfer function in $L_{max,Slow}$ 1/3 octave band. Vibration assessment between 5 Hz and 80 Hz. Noise assessment between 25 Hz and 500 Hz.

Building Foundation Coupling Loss

When vibration is transmitted from the ground into a building, a coupling loss may occur, whereby the level of vibration in the foundations is generally lower than that in the surrounding ground. Amongst other factors, the level of attenuation is dependent on the material impedance mismatch between the ground surrounding the structure and the foundation, and also on the characteristics of the building construction including the physical size and mass of the building and the footing design and foundation characteristics.

A range of attenuation values associated with various building categories is presented in [6]. These values are not directly applicable in the case of railway tunnels as they relate to the difference between "surface vibration levels" (ie what might be measured on the surface at a free-field development site) and "foundation vibration levels" (ie what might be measured once the new building has been constructed with the footings placed upon ground foundations at depth).

Moreover, the building foundations will be installed directly on the same rock bed as the railway tunnels. Thus, little or no material mismatch is expected between the surrounding ground and the structure's footings, as the structural concrete has similar mechanical impedance properties to that of the rock.

It was assumed that nil or very minor coupling loss will influence the train vibration entering building foundations at this site and therefore “0 dB coupling loss” was assumed in the predictions.

Floor Vibration and Noise Amplification

After vibration enters a building via the footings, amplification of some building elements may occur. The “flexibility” of walls, floors and ceiling elements results in higher vibration levels on room surfaces. A range of amplification factors for vibration due to the resonance of floors is presented in [6]; the mid values were adopted in the present *theskyvue* building vibration prediction process.

Slightly lower values are assumed for the ground-borne noise calculations as it is indicated in [7] that using the full floor amplification values can result in over-estimating the resultant noise.

Floor-to-Floor Attenuation

Losses also occur with the transfer of vibration from floor-to-floor within buildings (due to structural damping and geometrical spreading) and the predictions include floor-to-floor attenuation. A range of vibration attenuation values expected per floor is available from [6]. The common range of attenuation values is between 1 dB to 3 dB per floor with upper values generally applied to the higher frequencies.

Floor-to-floor attenuation is applied to predict the ground-borne noise and vibration levels in the retail spaces of the first three building levels, and in the office spaces from building level 4 and above.

Ground-borne Noise

The relationship between vibration and ground-borne noise is dependent upon a number of factors, including the amount of absorption within a room, the room size and shape, the variation in vibration level of the different sources and the radiation efficiency of the different surfaces.

For a given frequency, the linear weighted sound pressure level (in dB re 2×10^{-5} Pa) may be notionally estimated by subtracting 27 dB from the vibration velocity levels (in dB re 1×10^{-6} mm/s). This 1/3 octave band relationship between building vibration and ground-borne noise has been widely used [7] and has proven to be accurate on a large number of projects [8].

Noise A-weighting

The A-weighted ground-borne noise level in each 1/3 octave frequency band has been calculated by applying the standard A-weighting adjustments. The overall A-weighted noise level is then estimated by logarithmically summing the A-weighted sound energy levels across all 1/3 octave frequency bands.

THE PROBLEM

Heggies applied the detailed design methodology described in the previous section to predict the train induced ground-borne noise and vibration levels expected inside *theskyvue* building with no mitigation in place. The results are summarised in Table 2.

Table 2. Predicted train ground-borne noise and vibration levels – no mitigation. Noise levels expressed in $L_{Amax,Slow}$. Vibration velocity expressed in RMS values. VDV calculated using the 95th percentile train L_{max} vibration levels and based on 640 train events on the four underground lines and an average passby time of 15 s at an average speed of 45 km/h.

Indicator	*Occupancy*	*Predicted*	*Criteria*
Vibration Velocity Levels	Office	0.13 mm/s	0.4 mm/s
Vibration Dose Values	Office	$0.09\ m/s^{1.75}$	$0.4\ m/s^{1.75}$
Noise	Retail	57 dBA	50 dBA
	Office	50 dBA	45 dBA

While the vibration levels predicted with no building isolation in place complied with the project goals, the prediction for ground-borne noise significantly exceeded for all types of occupancy. This confirmed that audible ground-borne noise levels dictates the train induced vibration isolation requirements.

The noise levels of Table 2 would not be acceptable for the type of occupancies intended for *theskyvue* development - the exceedance was up to 5 dBA for the first affected office floor and 7 dBA for the lowest retail floor. In order to not significantly jeopardise the building usage and its economical viability, vibration mitigation was introduced as described in the following section.

THE SOLUTION

Building Base Isolation Requirements

It was decided that *theskyvue* vibration mitigation would be in the form of vertical and lateral vibration isolation bearings specially engineered for the project to ensure the future acoustic comfort of the building occupants. Discrete elastomeric bearings have been used to provide vibration isolation for many buildings constructed over railway tunnels, and have been found to provide good long-term durability and vibration isolation performance.

The base vibration isolation system of *theskyvue* building is inaccessible now that the building has been constructed, and therefore had to be designed to be durable and remain dynamically effective over the life of the building. It also has to withstand building loads and restrain lateral movement of the building caused by wind and earthquake loads. Heggies developed the complete set of specifications for the design, manufacturing and testing of the bearings. The main design requirements included dynamic to static tangent stiffness ratio, natural frequency, safe carrying capacity, stability, static compression stiffness and static shear stiffness.

An important aspect of the vibration isolation system was that the structural engineer was required to predict actual building loads which involved numerous intensive detailed analyses of the structure over and around the rail tunnels. For design purposes, the Normal Working Load (NWL) was defined as the structural Dead Load (DL) plus 30% of the structural design Live Load. The Maximum Design Load (MDL) was the sum of the Dead Load and the full structural design Live Load.

The performance of a vibration isolation system is dependent on the fundamental natural frequency, in addition to other factors. This design frequency is a function of the active mass and the dynamic stiffness of the bearing. One advantage of elastomeric bearings is that they contain inherent material damping, typically in the order of 5% critical. This limits the amplification at the system's natural frequency.

The natural frequency typically achieved by elastomeric bearings is in the range 7-9 Hz. Taking a simplifying assumption that active mass is lost to the isolation system as frequency increases (due to natural modes of vibration within the building), a relationship was developed to specify the insertion loss performance curves for *theskyvue* isolation system (Figure 9).

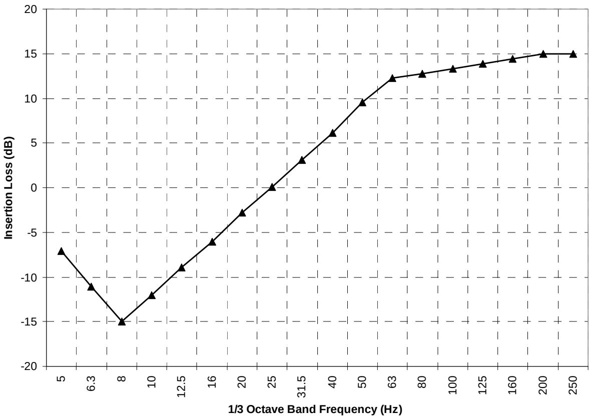


Figure 9. Building base vibration isolation system insertion loss requirements

System Description and Installation

The building base vibration isolation system of *theskyvue* consists of vertical and lateral elastomeric laminated bearings (also known as multiple sandwich bearings) installed at multiple locations on the building foundation level (Figure 10).

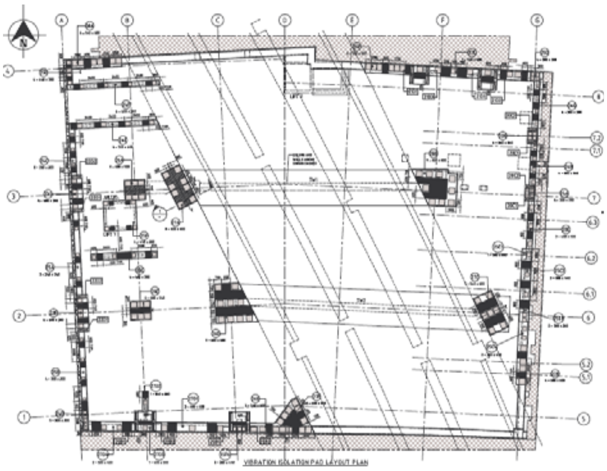


Figure 10. Vibration isolation layout at building footing level. A significant number of vertical bearings were used under the transfer walls across the tunnel easement. The rest of the bearing was distributed along the load bearing walls, columns and elevator shafts.

The bearings manufactured by Embelton are made of vulcanised natural rubber layers 'sandwiched' in-between multiple reinforcement steel plates (Figure 11). The lateral restraint bearings were pre-compressed with massive steel housings prior to installation (Figure 11); the housing restraints were released at a later stage to achieve the required bearing attenuation performance.

A stringent qualification test regime was carried out on the vibration isolation bearings to validate the compliance with Heggies specifications. Destructive safe carrying capacity testing (at 150% of MDL) as well as non destructive testing including static shear stiffness test and stability test was conducted for each type of bearing. All bearings underwent a static compressive stiffness test to validate the bearing deflection under design load and its dynamic properties (natural frequency). All batches of rubber material used to manufacture the bearings were tested to validate the following critical material properties: tensile and shear strength, hardness, resistance to creep under long term load and resistance to hostile environment.

Source: (Embelton, 2007)

Figure 11. Vibration isolation bearings. Left: vertical bearing. Right: lateral pre-compressed bearing with steel housing.

The construction of the footing system, part of the vibration isolation design, was very detailed. The design included insitu concrete pits which provide protection for the isolated footing structure. The footing pits were formed and poured against the rock strata. The isolation system included the vertical and lateral elastomeric bearings positioned at the base of the pit and void former was installed around the bearings and to the side of the pit to form the footings. Drainage to the footing pits was provided with drainage cell under the void former and drainage pipework connected to the central stormwater system. A fail safe system in the form of elevated concrete blocks was an integral part of the isolation system to support the structure in the highly unlikely event of catastrophic failure of one or several bearings (Figure 12).

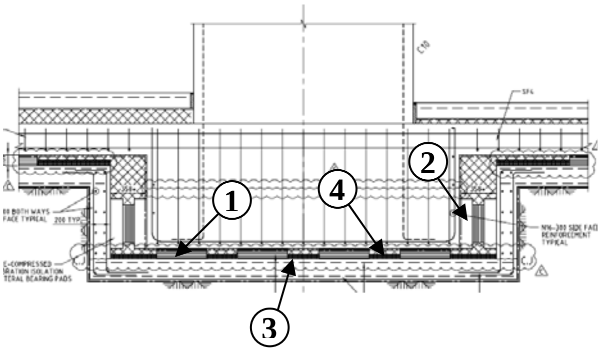


Figure 12. Typical pad footing details with vibration isolation bearings in place
1 - Vertical bearing 2 - Lateral pre-compressed bearing 3 - Water drainage system 4 – Fail safe block

Numerous site inspections were carried out by Heggies to ensure and certify that the vibration isolation system was correctly installed during the construction of the building. Figure 13 illustrates the installation of the the vibratin isolation system inside the footing pit.

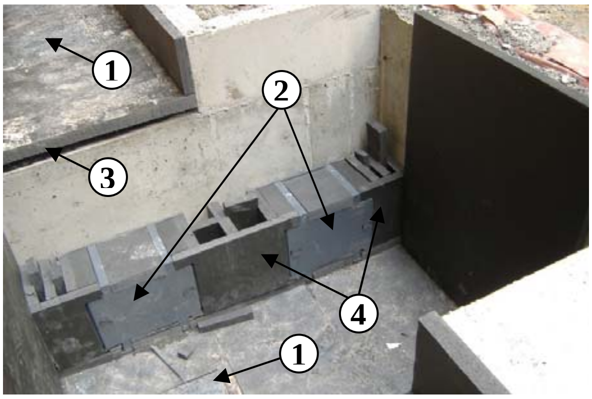


Figure 13. Installation of vibration isolation system . 1 - Vertical bearing 2 - Lateral pre-compressed bearing 3 - Water drainage system 4 - Void former around footing

Prediction Results

The insertion loss values specified for the base isolation system were included in the prediction methodology previously described to determine the levels of train ground-borne noise that would result inside the isolated building with mitigation (Table 3).

Table 3. Predicted overall levels of train ground-borne noise – with mitigation. Levels predicted at mid distance between York Street and George Street. Noise level expressed in $L_{Amax,Slow}$.

Occupancy	*Predicted*	*Criteria*
Retail	49 dBA	50 dBA
Office	42 dBA	45 dBA

Figure 14 presents the spatial distributions of the train ground-borne noise levels predicted on the first affected retail floor and the first affected office floor of *theskyvue* building with the specified vibration mitigation system in place.

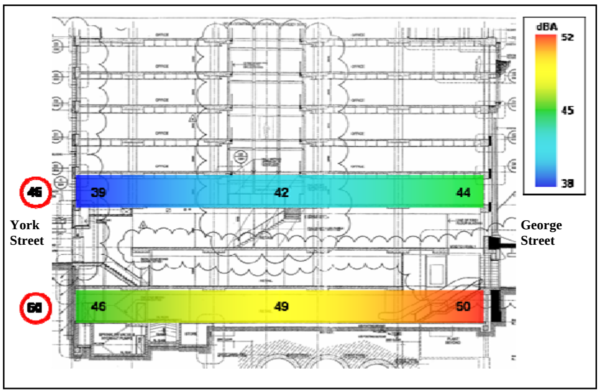


Figure 14. Predicted ground-borne noise levels – with mitigation

The predicted noise levels comply with both the retail and office noise criteria. As illustrated in Figure 14, there is little or no margin between the predicted levels and the criteria in spaces adjacent to George Street on both assessed levels. This is due to the significant contribution of the George Street retaining wall in transmitting train vibration into the building structure. The predicted noise levels decrease in areas further away from the George Street boundary.

COMPLIANCE MEASUREMENTS

Heggies conducted compliance noise and vibration measurements on the lowest retail floor and lowest office floor of the completed *theskyvue* building between March and July 2008. The noise and vibration levels were measured at a location directly above the railway tunnels (Figure 15). On the floor slab of Level 4 (the first affected office floor), the measurement location was approximately at mid-span between the building columns to capture the maximum floor vibration levels.

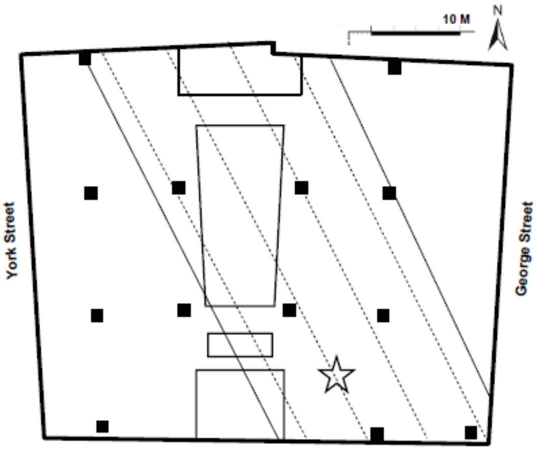


Figure 15. Top view indicating the location (☆) of the compliance noise and vibration measurements on the lowest retail floor and lowest office floor.

The measured overall ground-borne noise levels measured between 25 Hz and 250 Hz are presented in Table 4 and compared to the project goals and the predicted levels.

Table 4. Measured overall levels of train ground-borne noise – with mitigation. Levels measured at mid distance between York Street and George Street. Noise levels expressed in $L_{Amax,Slow}$.

Occupancy	*Measured*	*Predicted*	*Criteria*
Retail	49 dBA	49 dBA	50 dBA
Office	43 dBA	42 dBA	45 dBA

A very good correlation can be observed from Table 4 between the compliance measurements and the predictions made at the design stage. The 1/3 octave band frequency plot of Figure 16 further highlights the excellent correlation between predicted and measured ground-borne noise levels on the first affected office floor of *theskyvue* building.

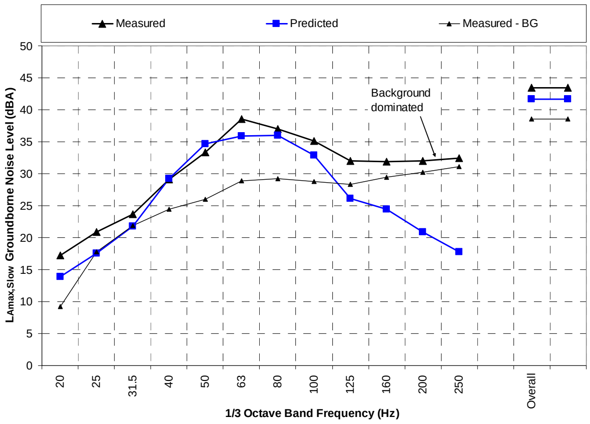


Figure 16. 1/3 octave band train ground-borne noise levels measured and predicted on the first office floor

A similar investigation was conducted on the train induced floor vibration levels. It was found that the predicted levels were consistently higher than the measured ones. The floor vibration levels are highly dependant on the dynamics and the deformation shape of the slab. Vibration levels are usually greatest at mid span and lowest near supporting walls and columns. In order to address this effect, the prediction methodology used by Heggies includes a floor vibration amplification factor due to the resonance of floors and the “flexibility” of walls, floors and ceiling elements.

While the compliance measurements were conducted at an approximate mid-span location, this might not represent the actual maximum of the slab deformation shape. It was found that, by removing the floor vibration amplification factor from the predictions, the predicted vibration levels then compared very well with the measured levels as illustrated in the plots of Figure 17 for the first affected office floor of *theskyvue* building.

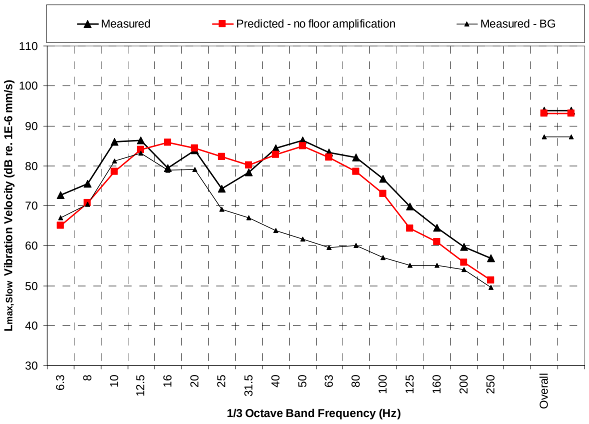


Figure 17. 1/3 octave band train induced floor vibration levels measured and predicted on the first office floor with no floor amplification

CONCLUSIONS

The building known as *theskyvue* recently completed at 413 George Street / 68 York Street, Sydney complies with the train induced noise and vibration project goals for the retail and office space occupancies. This represents a remarkable achievement as four active railway tunnels are located less than 3 m below the building’s foundations.

The process involved in successfully mitigating ground-borne noise levels inside the building included:

1. The measurements of free-field train vibration on the excavated site surface and retaining walls.
2. The implementation of an accurate detailed design hybrid model to predict train ground-borne noise and vibration inside the building.
3. The specification of a suitable building base vibration isolation system in the form of multiple discrete vertical and lateral elastomeric bearings.
4. The manufacturing of specially designed vibration isolation bearings.
5. The qualification testing of the isolation bearings.
6. The bearing installation design and inspections during the construction of the building.
7. The measurements of train induced noise and vibration levels inside the completed building to validate the prediction and check compliance with the design goals.

Several important observations were made during the project. It was noticed that the train vibration levels predicted inside the building were consistently higher than the levels measured during compliance testing. Whilst it is not possible to establish firm conclusions from a single project, it is suspected that the amplification factors used in the prediction of floor vibration levels were too conservative, especially outside of the suspended slab amplification frequency range (ie above 20 Hz). Using high amplification factors in the train induced vibration frequency bands (ie 50 Hz to 100 Hz) resulted in overpredicting the floor vibration levels inside the isolated building. It is also possible that whilst the vibration measurements were performed at the slab mid-span location, this might not represent the actual maximum of the slab deformation shape. Higher vibration levels might be measured at a different location on the slab, resulting in a better correlation between the predicted and measured levels.

Compared to floor vibration, the audible ground-borne noise represents a better spatially averaged indicator and remains in most cases the driving factor for the impact assessement and the detailed design of the building vibration mitigation system. For *theskyvue* project, an excellent correlation was obtained between the train ground-borne noise levels predicted at the design stage by the hybrid empirical-analytical model and the noise levels measured during compliance testing inside the completed building.

This confirmed that the adequate mitigation system had been successfully specified and installed. It also validated the ability of the hybrid model to accurately predict ground-borne noise levels from free-field train vibration measurements.

REFERENCES

1 International Strandard Organisation, ISO14837-1:2005, *Mechanical vibration — Ground-borne noise and vibration arising from rail systems — Part 1: General guidance* (2005)
2 Bassett Acoustics, *Development Application Acoustic Assessment – 413-421 George Street. Sydney, NSW*, prepared for Telado Pty Ltd, Report SA0288-gg-a1.rpt.rev02 (January 2005)
3 Australian Standard, AS 2670.2-1990, *Evaluation of human exposure to whole body vibration - Part 2: Continuous and shock induced vibration in buildings (1 Hz to 80 Hz)* (1990)
4 British Standard, BS 6472:1992, *Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)* (1992)
5 Rail Infrastructure Corporation (RIC) and the State Rail Authority (SRA), “*Interim Guidelines for Applicants – Consideration of Noise and Vibration in the Planning Process*” (2003)
6 P.J. Remington, L.G. Kurzweil and D.A. Towers, “Low-Frequency Noise and Vibration from Trains” in *Transportation Noise Reference Book* ed. P.M. Nelson, (Butterworths, London, 1987), Chapter 16.
7 The Association of Noise Consultants, *Measurement and Assessment of Groundborne Noise and Vibration* (Fresco, Great Britain, 2001)
8 T. Boxoen, R. Heggie and C. Weber, “Track for a clear way – Vibration control trackforms for tunnels in urban environments” *Proceedings of 33rd Permanent Way Institution Annual Convention*, Sydney, Australia (2006)