A DETAILED, TRI-AXIAL MEASUREMENT OF THE PERFORMANCE OF A BASE ISOLATED BUILDING IN LONDON DESIGNED TO PREVENT STRUCTURE BORNE NOISE AND VIBRATION FROM UNDERGROUND TRAINS

Tomasz Galikowski

Bickerdike Allen Partners, London, UK *email: tgalikowski@bickerdikeallen.com*

David Clarke

SRL Technical Services Ltd, Suffolk, UK *email: dclarke@srltsl.com*

Oliver Farrell

Farrat Ltd, Altrincham, UK *email: of@farrat.com*

This paper reports on a detailed study on the performance of a vibration base isolation system for an 8 storey steel frame education building in London which was built in close proximity to a shallow part of the London Underground Central Line. The study was a collaborative exercise between Bickerdike Allen Partners (BAP), who created the initial base isolation system specification, Farrat who designed, manufactured and supplied the vibration isolation system and SRL Technical Services Ltd.

The aims of the study were to: a) measure the actual performance of the isolated building to see how it performs in comparison with the predictions and b) use the results to better understand how base isolated buildings behave for future predictions.

Tri-axial measurements were taken at various positions at foundation / ground floor and 3rd floor levels (on isolated and un-isolated parts of the structure. Noise measurements also were carried out simultaneously on Level 2 and 3 (2 rooms near each vibration measurement cluster).

Results of these measurements were compared against the readings taken in the original un-isolated building which occupied the site prior to the construction of the new building.

Keywords: vibration isolation, ground-borne, noise, measurements

1. Introduction

1.1 Initial survey and predictions (2014)

A new Graduate Centre replaced former university buildings on a site located close to the Central Line (tunnel runs approximately 15 m south of the building) and Hammersmith and District Lines (in a cut-and-cover tunnel beneath Mile End Road, approximately 60 m away from the Centre).

Tube train vibration was expected to cause excessive ground-borne noise in the noise sensitive rooms – offices, seminar rooms, lecture theatres and library/reading room. Tactile vibration was not considered to be an issue. The following criteria, based on the Crossrail [1] noise performance specification have been adopted for the ground-borne noise assessment of the site. These limits apply to single pass-bys of London Underground trains.

Table 1: Summary of ground-borne noise criteria

Building	Daytime, dB $L_{A,s,max}$
Lecture theatres	35
Seminar rooms, offices, libraries	40

1.2 Initial survey and predictions (2014)

Noise and vibration were measured using the L_{eq} with a resolution of 1 second. The measurements were then processed to obtain logarithmic average over 5 seconds, with the peak located in the middle of this reference period. This index has been considered a more reliable and repeatable measure of train ground-borne noise than the $L_{A,f,max}$ level and is considered to be comparable to $L_{A,S,max}$ (typically within around 2dB).

Measurements were taken at various positions relating to future building, see figure below for locations:

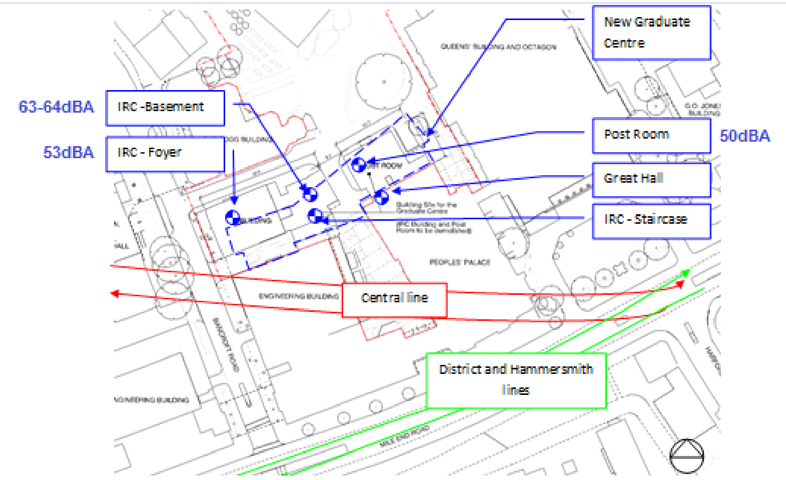


Figure 1: Initial acoustic survey – measurement positions and typical noise levels

Since the new building was designed to be a steel frame structure with lightweight, plasterboard partitions, noise measurements in the existing, masonry and concrete frame building were not applicable. Predictions of the re-radiated noise levels in the new development were based on theory concerning the radiation of sound power from panels as given in Annex C of BS EN ISO 140-4:1998 and based on the measured ground floor acceleration spectra. Predictions included building structure amplification and coupling between ground and structure. Calculated internal noise levels relate to those experienced at ground floor level. A conservative reduction of around 1 dB in structure borne noise per floor level going up was also included [5].

Noise was predicted to be between 50-53 dB in the East-Central part of the building and around 60 dB to the West, meaning an isolation of up to 20 dB was required to achieve the adopted criteria.

1.3 Building isolation

The eight-storey facility is constructed with a 750 tonne steel frame and concrete cores, a brick facade and curtain wall system.

The full building – base vibration isolation system comprised Farrat high performance natural rubber elastomeric bearings designed to match the loadings at each column and core point in the building (figure 2). The bearings were placed, levelled and grouted into place on each pile cap (Figure 3) and then reinforced concrete (RC) ground beams were cast on top of the bearings creating a matrix grid (Figure 4) which supported 250mm thick pre-cast-planks covered by a 50mm thick RC topping.

Figure 2

Figure 3

Figure 4

Figure 2: Bearings and shear keys installed on pile caps
Figure 3: Bearing installation with basic shuttering to pour supporting non-shrink grout bed
Figure 4: Ground beam grid matrix constructed on top of bearings

The bearings supporting the cores were specially designed to eliminate tension (and therefore the need to tension anchors) within the core walls. Specialist acoustic shear keys were used to limit the lateral wind induced shear to a maximum of 3mm. In the lift core an Isomat Floating Floor was constructed between the bearings and shear keys to cast the base slab as it was set lower than the stair cores meaning access after the base slab once poured was restricted.

The building included seven external V columns which spanned from pile cap level up to the underside of level 2. The steels of the V columns were diagonal and so the vertical load included a horizontal component which had to be resisted using acoustic lateral restraints.

Isofoam perimeter isolation material was used around the majority of the subterranean outer perimeter of the building where ground beams were cast directly up against existing buildings or where the ground was backfilled up against the threshold (Figure 5).

Figure 5

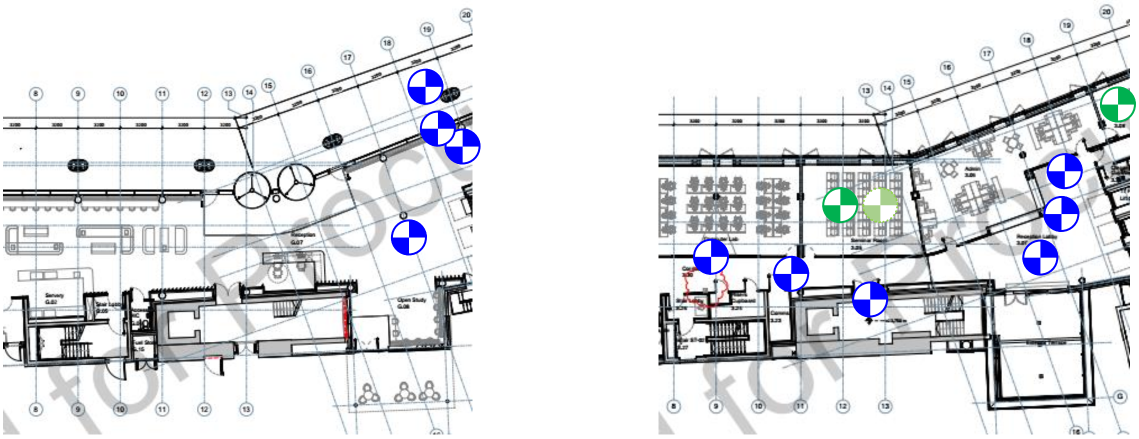
Figure 6

Figure 5: Isofoam isolation between subterranean structure and back-filled landscaping
Figure 6: Standard steel frame construction onto isolated ground floor

2. Post-completion survey (2016)

Just prior to completion, noise and tri-axial vibration was measured in the fully isolated building. Triaxial[1] vibration measurements were taken simultaneously at various locations on the Ground Floor and on Level 3, see figures below. Positions on the ground floor included un-isolated and isolated elements. On Level 3, locations included a mid-span and close to structural columns. Measurements were also taken in the un-isolated staircase linking the Graduate Centre with Engineering Building. Additionally, spot noise measurements were carried out at three positions on Levels 2 and 3.

[1] East-West (x-axis), North-South (y) and vertical (z)



Ground floor Third floor

NB: indicates vibrations measurements, noise measurements on 3rd floor and on 2nd floor

Figure 3: Post-completion survey –measurement positions. NB: vibration measurements are shown in blue, noise measurements are shown in green

3. Results

The measured vibration was converted to 5 second 1/3rd octave "Leq's" for each event to enable the direct comparison of the simultaneous measurements.

3.1 External vibration measurements

Externally, measurements were taken on the un-isolated pile cap at the foot of a "V-column" located outside the footprint of the ground floor of the building. Measurements were also taken on the steel column foot located directly above the building isolation pads, see photos:

Figure 4: Locations of External Measurements

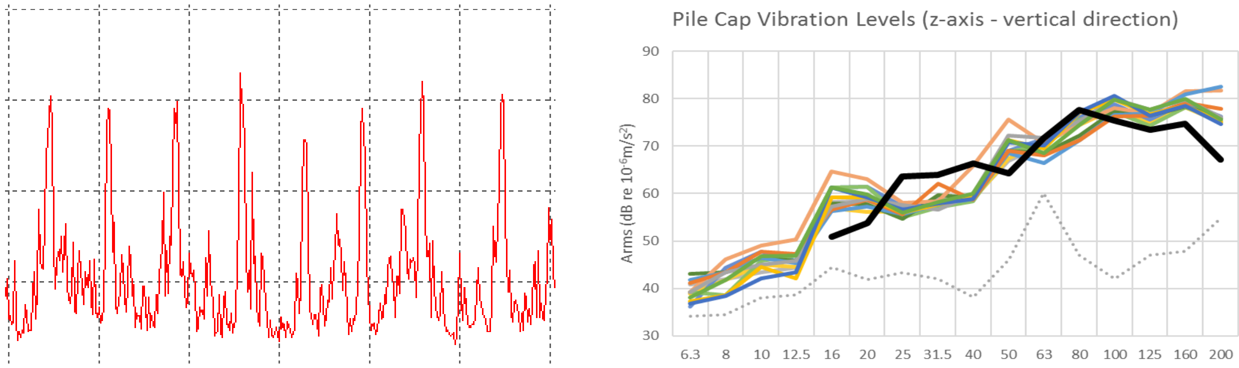


Figure 5: Time history and frequency analysis of several train events measured on the pile cap

Tube train events were consistent and clearly identifiable even though they could not be felt. The thick black line in Figure 5 above represents the typical vibration level measured in the basement of the previous building. The dotted line is the background vibration in the absence of any tube trains.

3.2 Base of V-column

Vibration levels measured on the foot of the V-column also provided consistent data, see figure below.

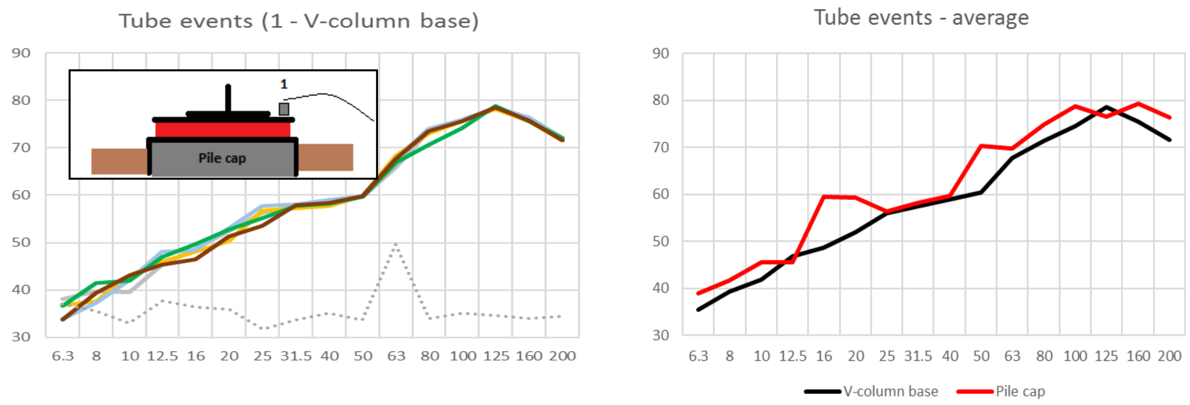


Figure 6: V-column vibration: Left chart - individual events; Right chart - average vs pile cap

The graph below shows the transfer function across the pad (in 1/3rd and octave bands) compared with the original predictions, based on the Building Amplification values - High and Low - from the Transportation Book [1] and the expected isolation from a rubber pad in a single DoF system:

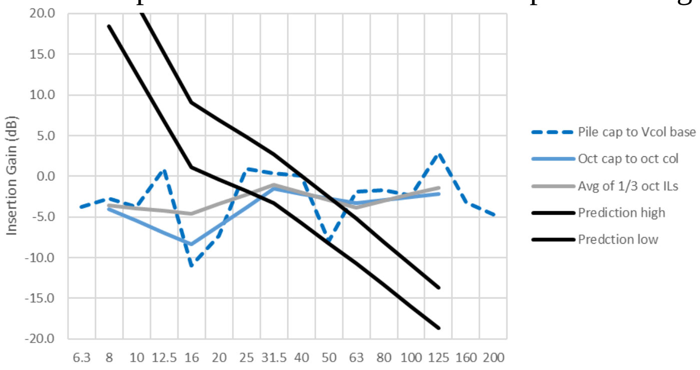


Figure 7: Measured and Predicted Transfer Function across the V-column pad

The actual performance is very “flat” compared with the predictions, showing neither:

- a prominent amplification at the pad resonant frequency (8Hz) nor
- the expected isolation at the higher frequencies

Indeed, there is barely any amplification at any frequency, other than peaks at 12.5Hz. 25Hz and 125Hz. The 12.5 Hz peaks are believed to be due to additional resonance, possibly introduced by horizontal bearings [3].

Furthermore, there is significant variation between adjacent 1/3rd octaves which is not evident in the octave band values of the Transportation book, a fact that needs to be appreciated by the would-be designer.

3.3 Vibration on ground floor

Vibration levels measured on the ground floor slab were very similar to the V-column foot values, with the exception of a peak at 63Hz which is consistent with the predicted fundamental frequency of the combined floor system [4].

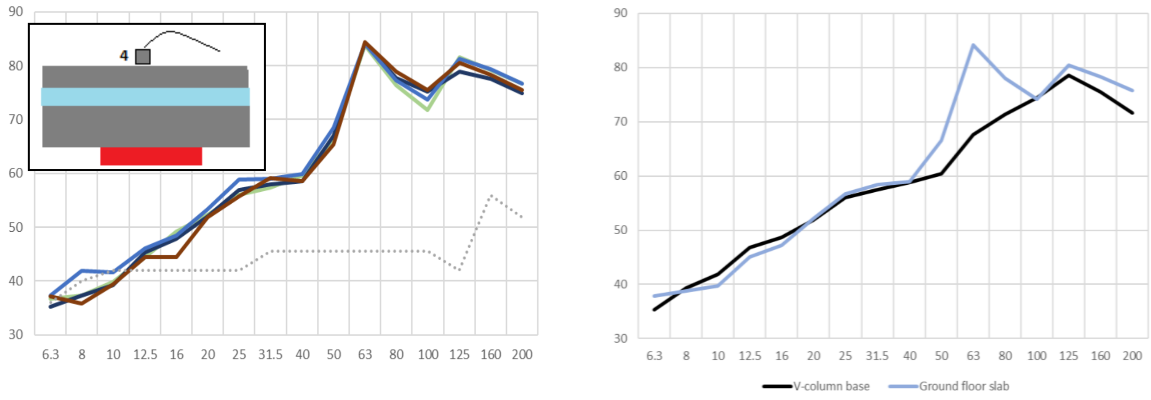


Figure 8: Vibration on GF slab: Left chart - individual events; Right - average vs V-column

Comparison of the Transfer Functions from the pile cap to both the V-column base and to the ground floor slab (see Figure 13) shows very consistent results other than at the 63Hz octave, which is thought to be affected by the floor resonance. This is a strong indication that the vibration across the base of the building appears to be a function primarily of the energy entering the building (via the pile caps and pads) and the effect of the superstructure of the building as a whole:

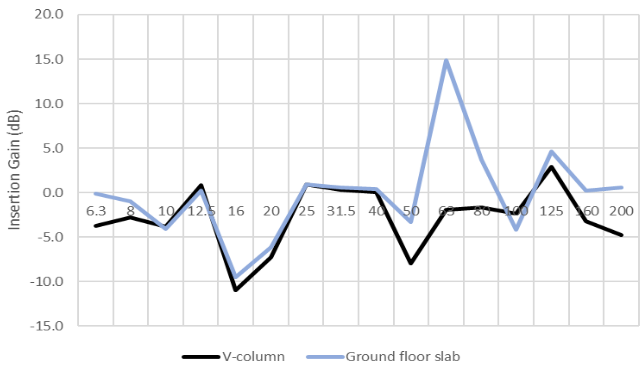


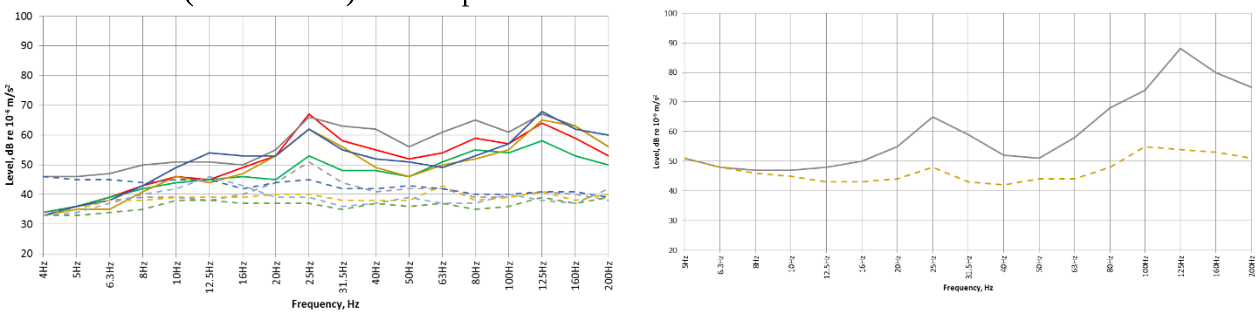
Figure 9: Transfer functions from the pile cap to different points at the base of the building

3.4 Level 3 results

No noise measurements were carried out in the former building on floor levels higher than ground floor, which makes evaluation of the insulation achieved difficult to assess. However, assuming that noise levels generally decrease by 2 dB per floor (as per [5], for example), this indicates a reduction of between 7 dB to 19 dB, depending on the room and reference noise level.

The results indicate that in most cases vibration in vertical direction is dominant. Graphs in Figure 10 below show a summary of vertical vibration survey results on Level 3.

Pos 1 (Grid 18-BB) – mid-span | Unisolated staircase



NB: Legend: solid lines – tube train, x-axis – red, y-axis – green, z-axis – grey; dashed lines – baseline

Figure 10: Summary of vertical vibration results – Level 3

All vibration measurements on Level 3 demonstrate a presence of peaks at 25 Hz and 125 Hz frequencies, the latter being caused by underground trains. The origin of the 25Hz peak is unknown. It could be a natural frequency of the steel framed structure or the first harmonic of the 12.5 Hz resonance prominent on the ground floor. It is also unclear why the 25 Hz resonance occurs in the un-isolated staircase. One of the explanations could be bridging between the buildings (e.g. due to polystyrene formwork) transferring vibration from the new structure to the older building.

Figure 11 compares transfer functions between un-isolated pile cap and isolated third floor vibration levels, and theoretical transfer function based on the high and low amplification values reported in [2] and the theoretical response of a 8Hz rubber pad in a single DoF system. In general, the measured performance follows theoretical curves decreasing at a rate of approximately 7 dB per octave. This is shown especially well on the octave band spectrum graph in Figure 11.

As observed earlier, there is no expected amplification at the resonance frequency of the pads with the values around 0 dB instead. At lower frequencies, the measured transfer function follows Lower Curve. At 25 Hz, the levels are amplified by around 10dB after which transfer function follows Upper Curve more closely. Transfer function measured at a positon near a column is generallywell below the Lower Curve.

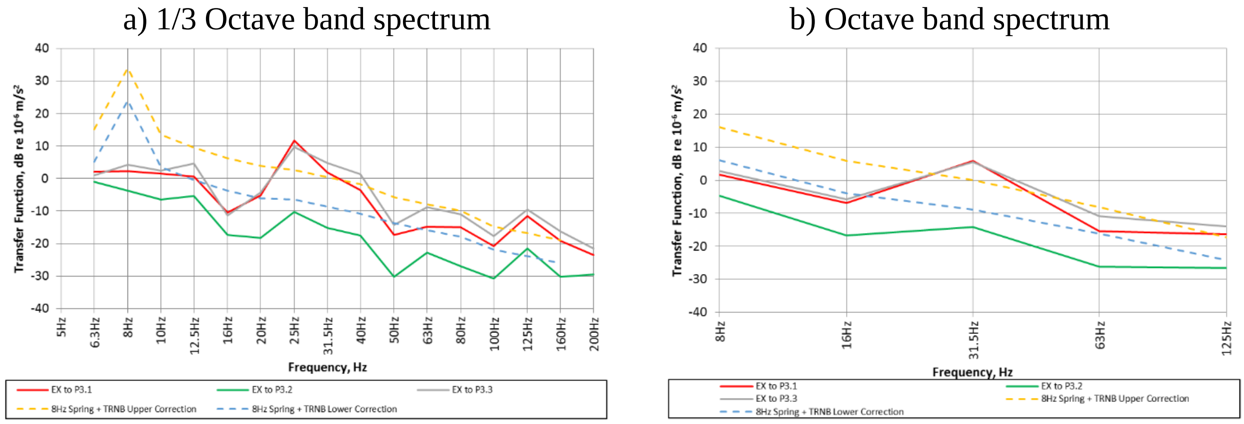


Figure 11: Transfer functions: external to third floor – field vs theory

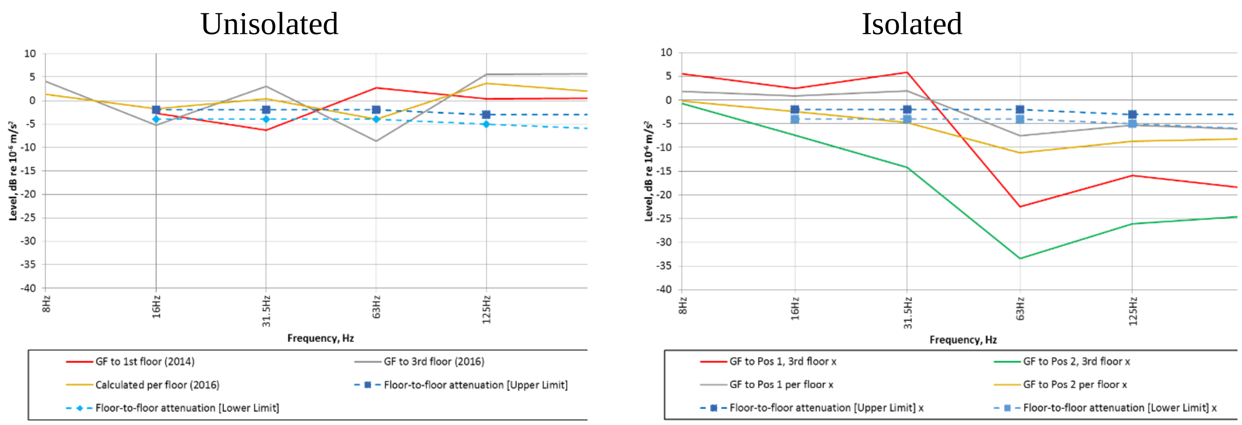


Figure 12: Attenuation per floor: field vs reference

The results discussed above demonstrates a difference between octave and third octave band analysis, with the latter, unsurprisingly, providing more detailed information. However, at the early stages of the projects, theoretical curves in octave bands appear to be sufficient in estimating expected vibration levels in the completed building.

Vibration levels generally reduce with height of the building. There is guidance available in literature on a typical rate of attenuation (e.g. [2]). Results of the 2014 and 2016 surveys allow comparison of field test data with the reference data, see Figure 12.

Difference in vibration levels on ground floor and third floor was divided by three to estimate attenuation per floor, as shown in [2]. For the QMU building, survey results in the un-isolated part corresponds well with the reference curve in the low frequency range but shows opposite effect in the higher frequency range indicating amplification. For the isolated data, however, the results generally follow theoretical figures with attenuation ranging from +2 (up to 31.5 Hz) to -11 dB attenuation across the frequency range. In overall, the theoretical figures would be on a conservative side.

4. Conclusions

One of the main purposes of the study was to determine if the isolation worked for intended purpose. The results of the survey indicate that the rubber pads reduced ground borne noise sufficiently, meeting the recommended criteria.

The results have been compared against the widely accepted prediction methodologies. Attenuation per floor has been found generally in line with the literature. The prediction from pile cap vibration to upper floors is also within expectations, but not apparently to the ground floor. It is possible that any reductions has been cancelled out by either bridging (e.g. during construction) or building amplification.

The survey results did not reveal the large amplification predicted at the pad resonant frequency, however, an unknown resonance at 25Hz has been identified and needs further investigation.

Analysis of the results suggest that for all practical purposes, vibration in vertical direction is sufficient to predict and design building isolation, with horizontal vibration contributing significantly less energy. It has also been found that use of octave bands should be treated with caution due to large differences between adjacent 1/3 octave bands. However, at early stages of the project, octaves would be sufficient in determining basic vibration isolation requirements.

It should be noted that the results of this survey are more applicable to steel frame buildings with concrete slabs.

5. Further work

It is proposed the next step will involve modelling the building in an FE package to investigate cause of 25Hz peak and also the effect of making changes to the design (e.g. replacing steel frame with concrete frame). Thorough modelling will also be used to understand how (and to what extent) changes to the design parameters (such as stiffness and mass of building elements, junction details, etc.) affect the predictions.

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