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THE USE OF TRIAL PILES IN ASSESSMENTS OF GROUND-BORNE VIBRATION

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As the design of modern buildings continue to deviate further from pre-1970 designs, so too have the analytical means by which to assess them, particularly in scenarios where structures are subject to base-excitation from underground rail networks. Though such advances bring welcome and necessary change, precision dictates that source-soil and soil-structure interaction is appropriately accounted for. These effects can be simulated via numerical methods, however the determination of all pertinent transmission mechanisms and their uncertainties can be challenging and would require accompanying measurements to calibrate / validate the model nonetheless. In the absence of a simulation environment, the use of surface vibration measurements in positions within the proposed development footprint, subsequently manipulated via empirical building transfer functions are common. This procedure risks overlooking subterranean effects in areas where transmission via, for example, pile-toes, may dominate. An alternative approach is to undertake measurements upon trial-piles to approximate the behaviour of actual building piles in the final construction. Measurements undertaken in this way have the possibility of gathering the range of uncertainties inherent within the source-structure transmission path. If proven effective, such measurements could be of benefit to a wider scope of practitioners, particularly those whose computational modelling resources are limited. This paper summarises the results of trial pile measurements undertaken on a brownfield site, poised to make way for new-build construction and situated above a section of the London Underground rail network. Comparison between on-pile and ground-surface measurements is presented in addition to an assessment of vibration levels within the main structural form. The latter aspect having the added benefit of providing comment on the validity of empirical transfer functions that are so often relied upon.

Keywords: Vibration, measurement, prediction, uncertainty

1. Introduction

When subject to groundborne vibration from underground rail systems, theoretical models of vibration propagation within the proposed receiving structure are of vital importance to the early design and in many cases, the ultimate goal of deciding on whether or not to incorporate base isolation is difficult to conclude given the uncertainties in measurement and prediction approaches. Further, as base isolation is expensive and often difficult to implement, it is preferable to avoid such measures where possible.

Current guidance, such as that which is provided within the Association of Noise Consultants 'Red Book' [1] stipulates that a practitioner should take care when undertaking such measurements on open sites as there is a potential for buried structure, concealed ground slabs for example, to adversely skew measurement findings. Hidden elements of construction could perceivably increase measured levels if acting as a coupling mechanism to vibrational sources which would be removed during construction. Conversely, the same element may present additional impedance, local screening or other forms of modification to incident vibrational wave motion. Once removed, this may result in greater energy at the receiving point of interest than originally observed.

Without prior knowledge of ground conditions, overlooking effects of vibration performance with depth may also result in misrepresentative characterisation of the local vibration field, particularly in the vicinity of any proposed pile toes which can admit high levels of energy into a structure.

This paper presents a case study of measurements obtained at a site over a number of years from original scoping measurements at grade to assessment within the completed superstructure. In particular, attention is drawn to a series of measurements conducted on a trial pile in the attempt to better quantify soil-to-pile transfer mechanisms and therefore reduce uncertainty in both measurement and prediction aspects of an engineering-grade assessment. Focus is made with regards to vibration levels in the third-octave band frequency range spanning 20Hz to 315Hz, as such levels typically form the basis for predictions of re-radiated noise in dwellings or other noise sensitive spaces. The aims of this paper are thus:

1) To illustrate the variation between measurements conducted at grade to those undertaken on the trial pile cap (also situated at grade).
2) To present the difference in measurement level within a completed building and compare the findings to those carried out in the building's absence.
3) To comment on potential impact of adopting transfer function correction factors on both data sets when seeking to predict soil/structure interaction and the effects of building response.
4) To comment on the validity or perceived benefits of utilising trial piles as a means to assist assessments of groundborne vibrations in new-build structures.

2. Measurements at grade

Early scoping measurements of a brownfield potential development site were undertaken using a single channel Vibration Level Meter (VLM). Rolling 1-second RMS acceleration measurements, with appropriate detector settings were captured so as to provide slow-weighted maximum vibration levels for use in predictions of re-radiated noise, represented using the common $L_{Amax,S}$ metric. The site is affected by vibration from two underground rail lines however the measurement signal from the line closest to the proposed development site was clearly in excess of that with the higher source-receiver separation. As such, only the higher values are reported and remains the case throughout this paper.

A sample comprising 27 train pass-by events were recorded at one position (Position 1) with an additional 11 pass-by events obtained at a secondary position (Position 2). Third octave acceleration values are provided in Figure **1** and Figure **2**. Table 1 provides broadband acceleration values in terms of arithmetic mean and mean +/- 1 standard deviation. It can be inferred from both figures and the associated table that both positions exhibit reasonably consistent levels over the sample population.

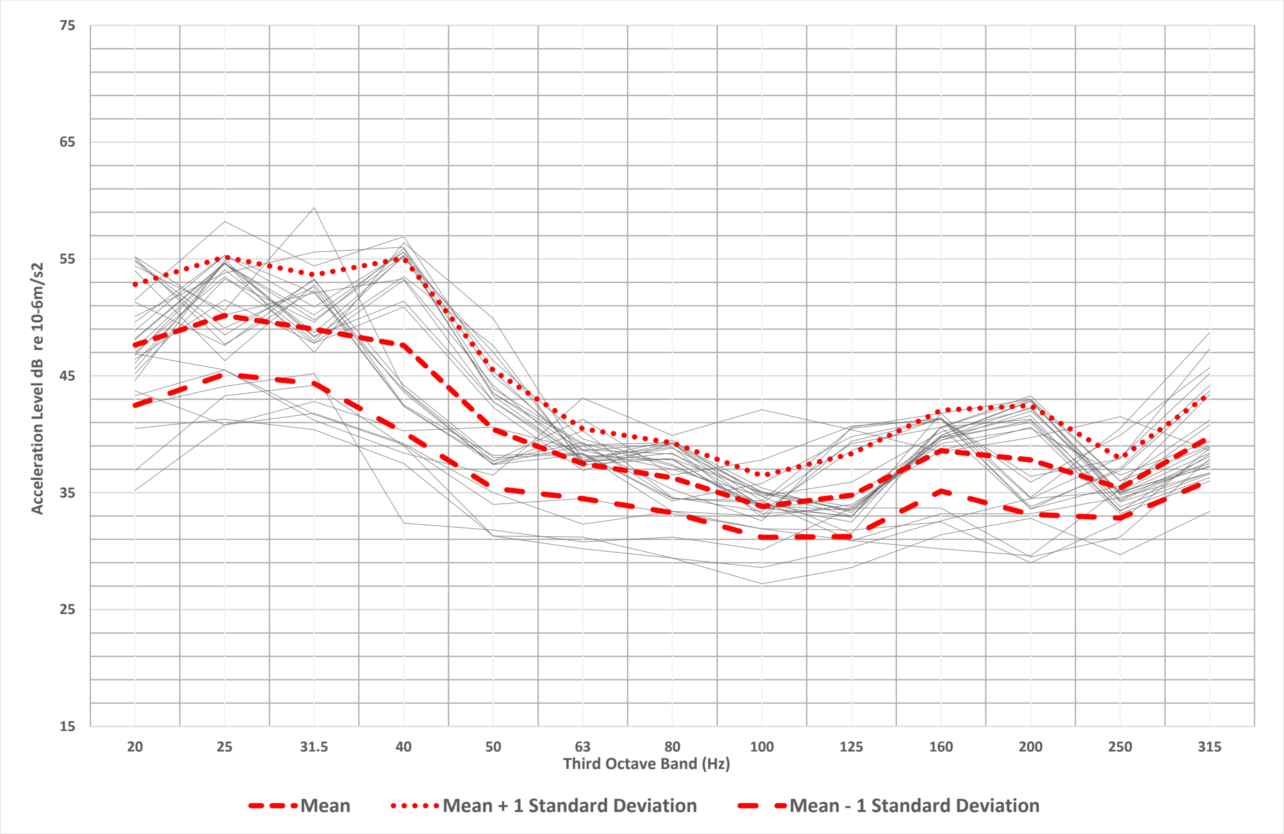

Figure 1: Measurement position 1 (Grade)

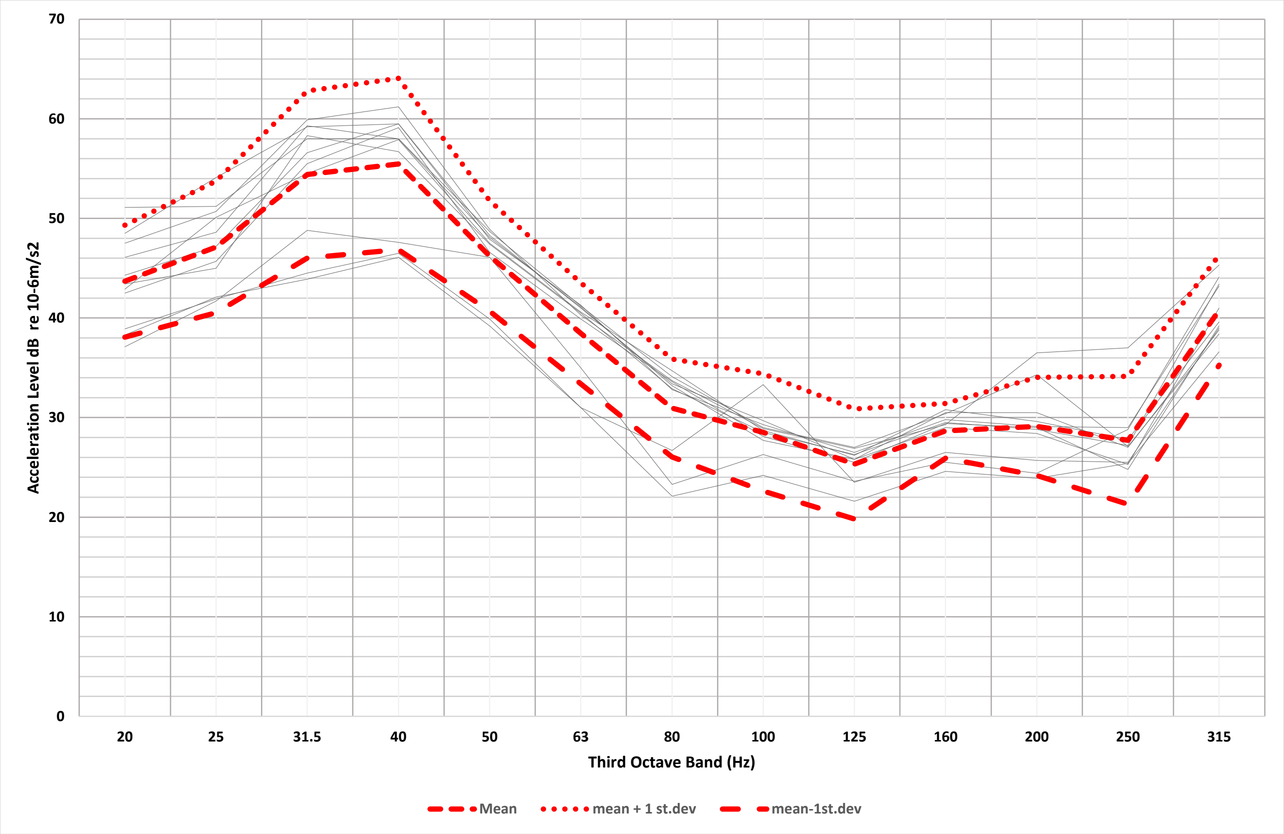

Figure 2: Measurement position 2 (Grade)

Table 1: Summary of broadband acceleration level

	Acceleration Level ($dB\ L_{max,S}$ re $10^{-6}\ m/s^2$)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
1	57	4	61	53
2	60	4	64	55

2.1 Predicted re-radiated noise

2.1.1 Pseudo groundborne levels

Third octave band arithmetic mean and mean +/- 1 standard deviation acceleration values (1s slow max metric) were used within formulae to predict re-radiated noise within a room due to vibration of floors. The governing equation assumes that levels of acceleration are spatially averaged and the radiation efficiency of elements subject to vibration would be equal to unity. Predicted values for measurements at ground positions P1 and P2 are summarised in Table **2**.

Whilst it is acknowledged that this prediction mechanism does not fully describe coupling between structural and fluid media (and vice-versa), nor accounts for the spatial variation in sound pressure level within a room, it remains a method commonly used by engineers therefore use is maintained herein so as to allow common comparison between data sets. Values for vertical (z-axis) are presented to allow comparison with the original vertical orientation measurements of the scoping exercise.

Table 2: Summary of re-radiated noise level predictions based on P1 and P2 acceleration levels

	Predicted Re-Radiated Noise ($dB\ L_{Amax,S}$ re 20×10^{-6} Pa)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
1	12	3	15	9
2	13	3	16	9

Though not of particular importance to this paper, the proposed development, being a residential scheme, would be compliant with a 35dB $L_{Amax,S}$ criterion that is typical for new developments in the Greater London area.

3. Trial-pile measurements

Boreholes required as part of civil / structural groundwork investigations provided an opportunity to conduct further measurements on site, with the end client agreeing to facilitate backfilling with concrete using a small diameter casing. The depth of the borehole was equal to that of proposed piles and once poured, concrete was levelled off at grade to form a smooth finish allowing placement of sensors in the correct orientation.

A sample comprising 11 events is illustrated within Figure **3** and includes third-octave arithmetic mean and ‘mean+/- 1 standard deviation’ values. The third-octave band profile follow the same general trend as observed in Figure 1 and Figure 2, and individual pass-by events exhibit good agreement.

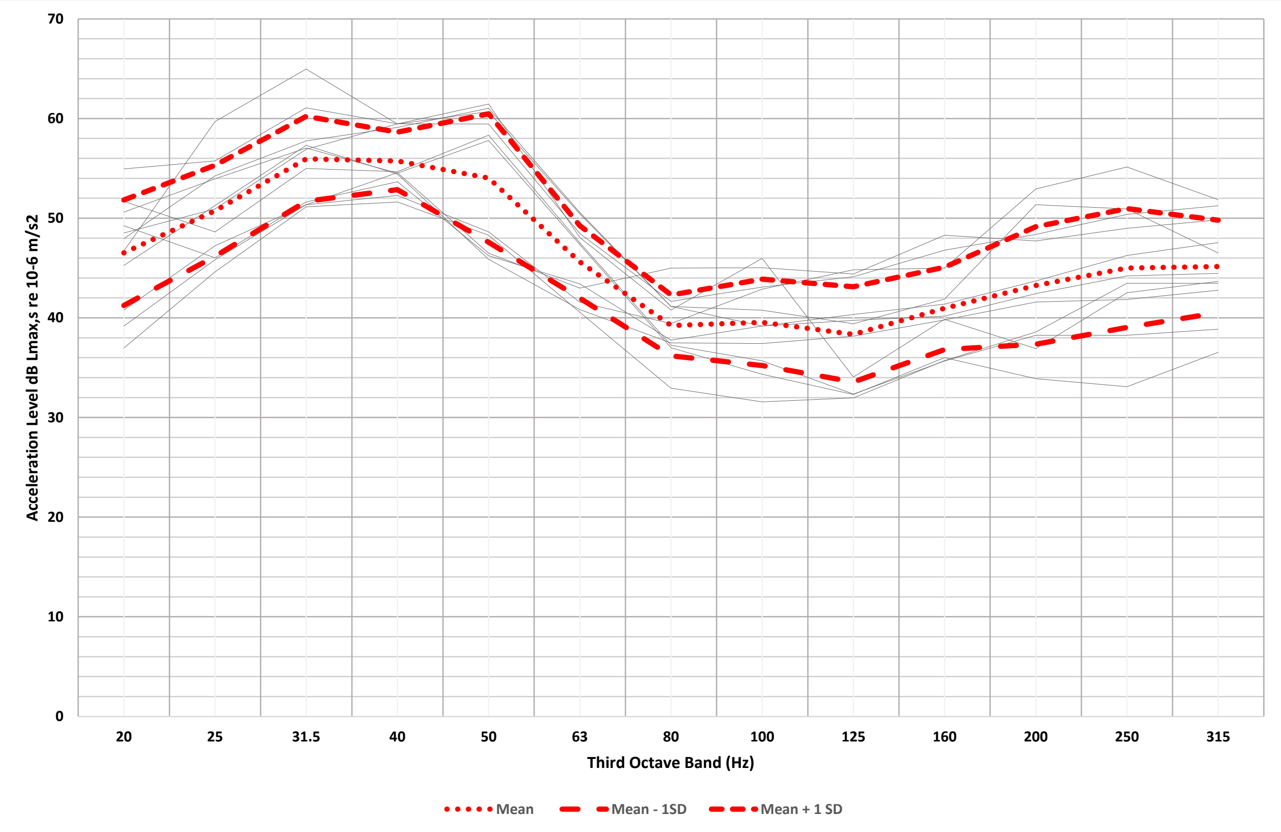

Figure 3: Summary of trial-pile / borehole measurements

Broadband acceleration measurement values and associated predictions of re-radiated noise are provided in Table **3** and Table **4** respectively. Comparison to measurements at grade (Table **1** and Table **2**), suggests that whilst there is a modest increase in overall acceleration, predictions of re-radiated noise increase by up to 6dB. This is due to an increase in acceleration at bands above 100Hz, which have a greater influence upon the overall A-weighted value. Differences of this magnitude are considered to be significant and if overlooked in assessments where the need for base isolation was considered to be borderline, it follows that future problems may potentially arise in occupied buildings if no further scrutiny of the vibration climate was undertaken during the progression of the scheme design or construction.

Table 3: Summary of broadband acceleration levels – trial pile location

	Acceleration Level (dB $L_{max,S}$ re 10^{-6} m/s^2)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
Trial Pile	62	3	65	59

Table 4: Summary of broadband re-radiated noise level predictions – trial pile location

	Predicted Re-Radiated Noise (dB $L_{max,S}$ re 20 x 10^{-6} Pa)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
Trial Pile	18	3	21	15

4. Measurements within the superstructure

Within the completed superstructure, measurements were undertaken upon the suspended ground floor level slab in the general vicinity where scoping and trial-pile measurements were carried out previously. Mid-span locations were selected with the aim of subjecting the sensors to maximum vertical displacement. Figure **4** summarises third-octave band measurements and includes mean and mean+/- 1standard deviation spectra. Associated predictions of re-radiated noise based on these values are provided in Table **5**and Table **6**.

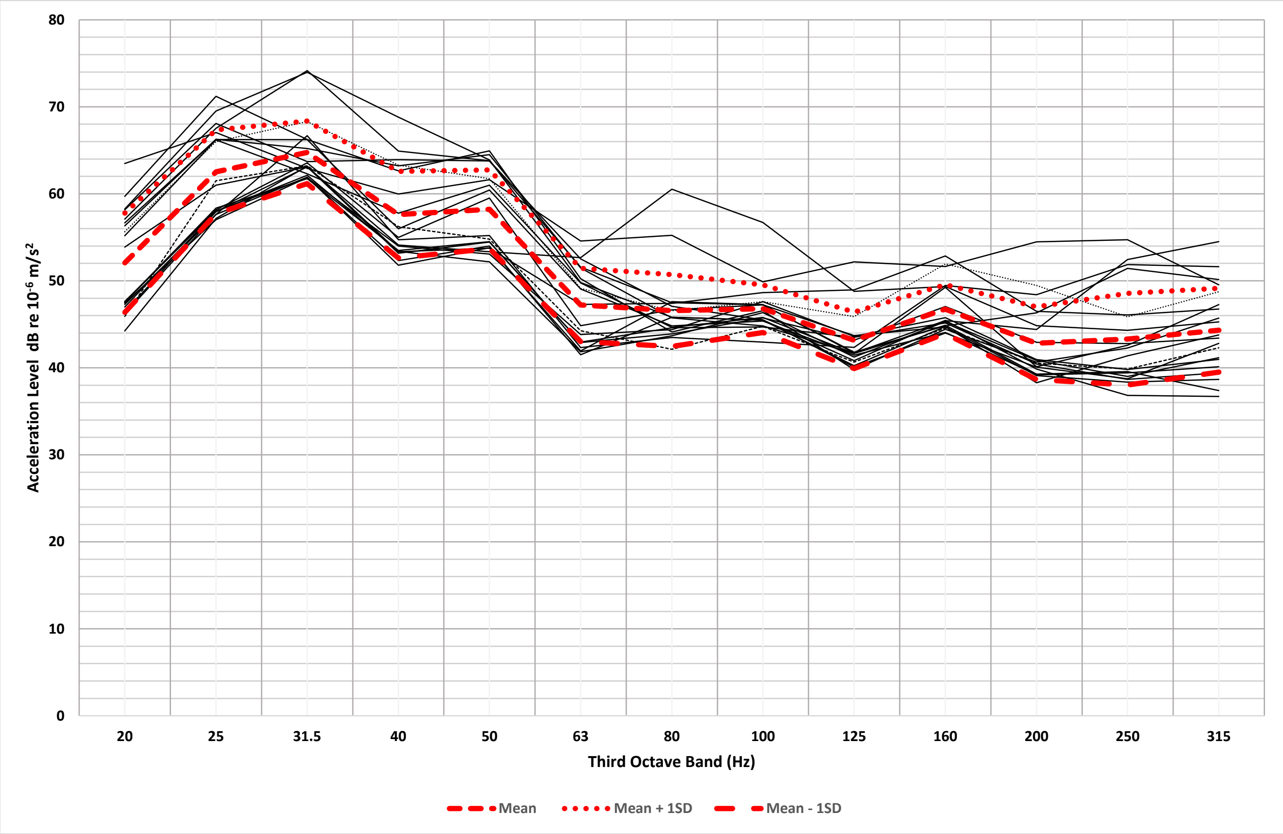

Figure 4: Summary of in-building vibration measurements

Table 5: Summary of broadband acceleration levels – In-building location

	Acceleration Level (dB $L_{max,S}$ re 10^{-6} m/s^2)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
Structure	69	4	73	65

Table 6: Summary of broadband re-radiated noise level predictions – In-building location

	Predicted Re-Radiated Noise Level (dB $L_{max,S}$ re 20 x 10^{-6} Pa)			
Position	Mean	Standard Deviation	Mean +1 SD	Mean -1SD
Structure	22	3	25	19

5. Comparison between results

Figure 5 provides a comparison of re-radiated noise level predictions for each measurement scenario. It is evident that the trial pile measurement position presented a better representation of vibration within the completed building. Trial-pile pseudo noise level predictions were 4dB lower to that which were obtained from in-building measurements. Predictions based on solid ground vibration data resulted in pseudo noise levels between 10-11dB lower to the in-building value.

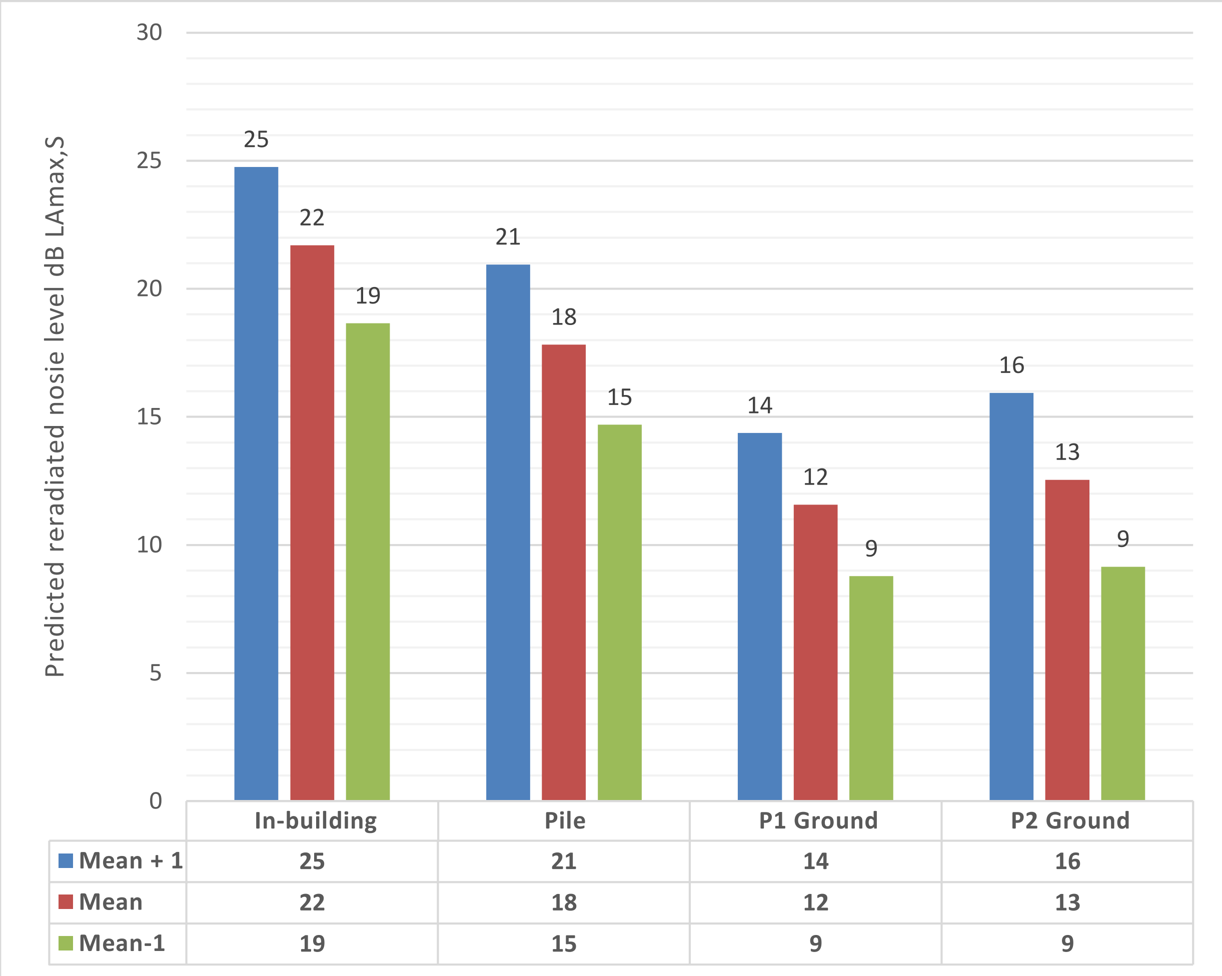

Figure 5: Comparison of re-radiated noise values

5.1 Additional considerations

Though a 4dB disparity between trial-pile and in-building values may be sufficient as a first-order assessment of vibration or groundborne noise, there are many additional factors which can influence actual in-situ levels. Traditionally, these matters were accounted for via empirical transfer function corrections and building response adjustments to account for interaction between soil and structure in addition to the mobility of the proposed building. These empirical factors, having been developed many years ago, arguably do not best represent the modern, lighter and potentially more dynamic forms of construction and consequently, their use should be treated with caution.

Common corrective values, such as those suggested by Nelson [2] vary with construction type. The most appropriate grouping for the development considered in this paper is that of 'Large Masonry on Piles' with possible further correction options to account for potential effects of floor resonance.

With regards to the latter, a choice of 'low' or 'high' amplification factors are available to the practitioner undertaking calculations.

Accounting for these aforementioned aspects can result in a +6dB increase in broadband vibration (at worst) to -1dB attenuation (at best) depending on the level of amplification chosen. The impact this has on re-radiated noise however is marginal in this case as most adjustments are constrained to lower frequencies which have a lesser impact on the overall A-weighted value. In any case, such corrections serve to marginally improve the agreement shown between trial-pile assessments and those of the in-building condition.

If one chooses to adopt 'aspects' of empirical corrections, such as including building transfer functions but neglecting floor resonance and vice-versa, then variations of vibration and pseudo noise level predictions can be expected to easily vary between +/-10dB and as such, measures should be taken, preferably by measurement and alongside more refined methods of calculation, to iteratively converge on a final assessment value that reduces degrees of uncertainty.

6. Conclusion

As a means to forming an improved engineering grade assessment of groundborne vibration in buildings, the implementation of trial piles is observed to provide, in this case at least, a better indication of vibration levels in the proposed completed structure than measurements on solid ground alone.

There is a question mark over the validity of continued use of empirical transfer functions within modern construction forms. However, there may be merit in using the various combinations as a means to account for uncertainty. Unfortunately, the range of uncertainty values could feasibly lie in the region of +/-10dB, which may make a definitive assessment outcome problematic.

It is hoped that measurements on trial pile arrangements, though rare in occurrence, could be used to facilitate better precision in harmony with more advanced forms of analysis.

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