Structureborne Noise Assessment

Buildings W1 and W2
Development Zone W (Triangle Site)

King's Cross Central
General Partner Ltd

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King's Cross

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1. EXECUTIVE SUMMARY

Ramboll Environ has been appointed to undertake a detailed assessment of structureborne noise affecting the Proposed Development within the Triangle Site (Development Zone W), part of King's Cross Central (KXC) Development.

The scope of the assessment is to demonstrate how the proposed residential Buildings W1 and W2 will comply with Condition 29 of the Triangle Outline Planning Permission (Secretary of State's references APP/V5570/A/07/2051902 and APP/X5210/A/07/2051898[1]).

The condition requires the applicant to demonstrate that structureborne noise level inside dwellings will not normally exceed 35dB $L_{Amax,s}$.

Buildings W1 and W2 are to be located in close proximity to the Thameslink Canal Tunnels (TCT) and the East Coast Main Line (ECML). In order to assess the effect of structureborne noise, Ramboll has undertaken detailed vibration analysis. Building W1, which is subdivided into Building W1 West and W1 East, is the closest to both the TCT and ECML. Therefore, only building W1 has been assessed since Building W2 will meet the required criteria if Building W1 does.

The works include vibration measurements and assessment of the impacts of ECML and Finite Element Modelling to determine the effects of the TCT which are expected to be operative in late 2015/early 2016.

The results show that as Network Rail has used a 'soft' High Attenuation - Low Vibration Track (HA-LVT) for the rail tracks within the TCT, the predicted structureborne noise levels inside Building W1 are expected to be below 35dB $L_{Amax,s}$ In addition, the results of the vibration measurements undertaken to assess the effect of the ECML show that there will be limited impact and therefore Building W1 will meet the required criterion.

The assessment therefore demonstrates that structureborne noise inside the proposed development will be within the requirements of the London Borough of Islington and the London Borough of Camden as detailed in the Triangle Outline Planning Permission and hence enables full discharge of the planning condition on structureborne noise that is currently imposed on the development.

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[1] London Borough of Islington - *Application Reference: P041261* and London Borough of Camden - *Application Reference: 2004/2311/P (Triangle Outline Planning Permission)*

2. INTRODUCTION

The excitation of floors and walls generated by the propagation of vibration can give rise to audible low frequency noise. Such noise is defined as structure-borne noise.

Buildings W1 and W2 within the Triangle Site are to be located between the Thameslink 2000 Canal Tunnels (TCT) and the East Coast Main Line (ECML). Therefore there is a risk that structure-borne noise could negatively affect the proposed development.

This report summarises the results of vibration measurements and computer modelling undertaken by Ramboll Environ to assess the impact of structureborne noise on the proposed development.

3. PLANNING CONDITIONS AND NETWORK RAIL COMMITMENT

The planning permission pursuant to the application submitted to the London Borough of Islington - *Application Reference: P041261* and London Borough of Camden - *Application Reference: 2004/2311/P (the "Triangle Outline Planning Permission")* includes the following condition on structureborne noise level inside dwellings:

> *Condition 29*
>
> *"Before development commences, a scheme shall be submitted to and approved by the Local Planning Authority to demonstrate how the proposed dwellings would be insulated to a standard that will ensure that internal groundborne noise levels do not normally exceed 35dB(A) $L_{max,s}$. The dwellings shall be constructed in accordance with the scheme, as approved unless otherwise agreed in writing by the Local Planning Authority".*

In the construction of the Tunnels, Network Rail committed to use Best Practicable Means so that ground-borne noise levels in residential dwellings would not exceed 40 dB $L_{Amax,s}$ which is 5 dB higher than Condition 29 (above).

To meet the 40 dB criterion, Network Rail installed a 'soft' Low Vibration Track (LVT) in combination with soft block pads (to provide High Attenuation), or HA-LVT.

4. SITE AND PROPOSED DEVELOPMENT

The Triangle Outline Planning Permission was granted on 22 July 2008 by the Secretary of State with references P04161 (London Borough of Islington) and 2004/2311/P (London Borough of Camden) (the 'Triangle Outline Planning Permission').

Development Zone W (referred to as the Triangle Site) sits on the northern periphery of King's Cross Central (KXC) to the north of York Way, defined on all boundaries by key pieces of road and rail infrastructure, namely York Way, Thameslink tunnels and track, the East Coast Mainline and Randell's Road.

The Triangle Outline Planning Permission permits 3 buildings – W1, W2 and W3 (referred to within the Triangle Outline Planning Permission as Block A, B and C, respectively) – located around a new central garden space with landscaped areas to the north (the Ecology Garden) and the west (the Northern Gateway).

The current proposals seek reserved matters approval for the two residential buildings, W1 and W2. Building W1 will comprise a 12 storey (W1W) and 17 storey (W1E) building providing 140 open-market residential apartments in total, along with a single retail unit at street level fronting onto York Way. Building W2 will comprise 8 storeys of mixed tenure residential accommodation providing 36 social rented apartments, 23 intermediate apartments and 19 open-market apartments. Three retail units will provide active frontage and animation along York Way. The buildings share a single level, part basement, part lower ground floor which provides ancillary space and cycle/car-parking from a new access road from York Way.

Building W3 is proposed under the Triangle Outline Planning Permission to be for leisure uses (D1/D2). Detailed proposals for this building are still under development and the submission of an application for reserved matters approval relating to this will follow in due course. Similarly, the landscaping and public realm details will be submitted at a later date for reserved matters approval.

Non-material amendments to the internal layout and shoulder heights of Buildings W1 and W2 are being sought under a separate application pursuant to Section 96A of the Town and Country Planning Act.

The development zone and adjacent infrastructure are shown Figure 1.

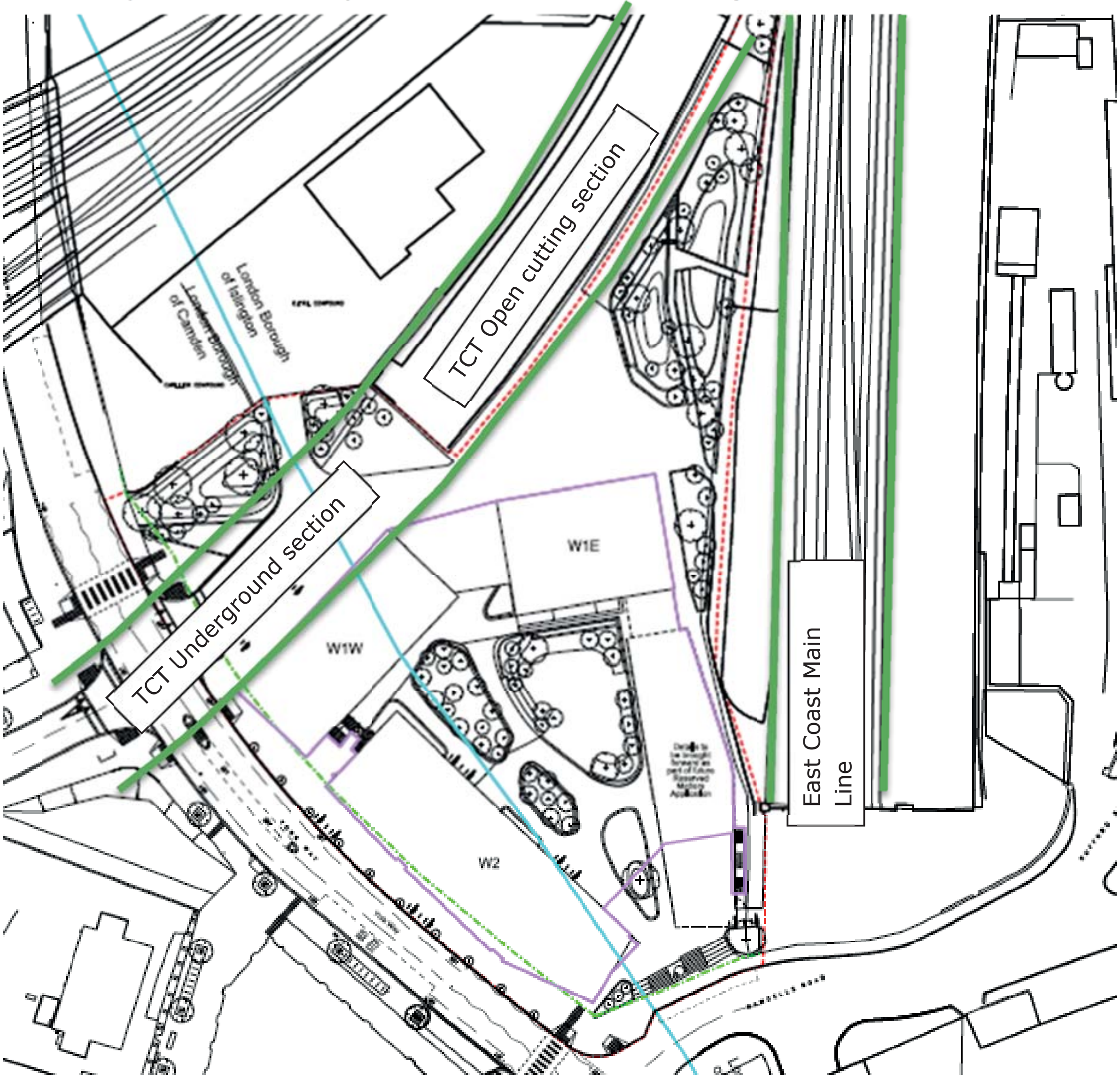

Figure 1 Development Zone W and adjacent infrastructure

5. EAST COAST MAIN LINE ASSESSMENT

A vibration survey was undertaken by Fabrizio Filippi CEng MIOA and Christina Higgins AMIOA of Ramboll Environ on Tuesday 20th January 2015. The vibration monitor was set to measure vibration levels between 10:30 am and 12:30 pm. Both VDV and un-weighted accelerations were measured. The measurement position is shown in Figure 2.

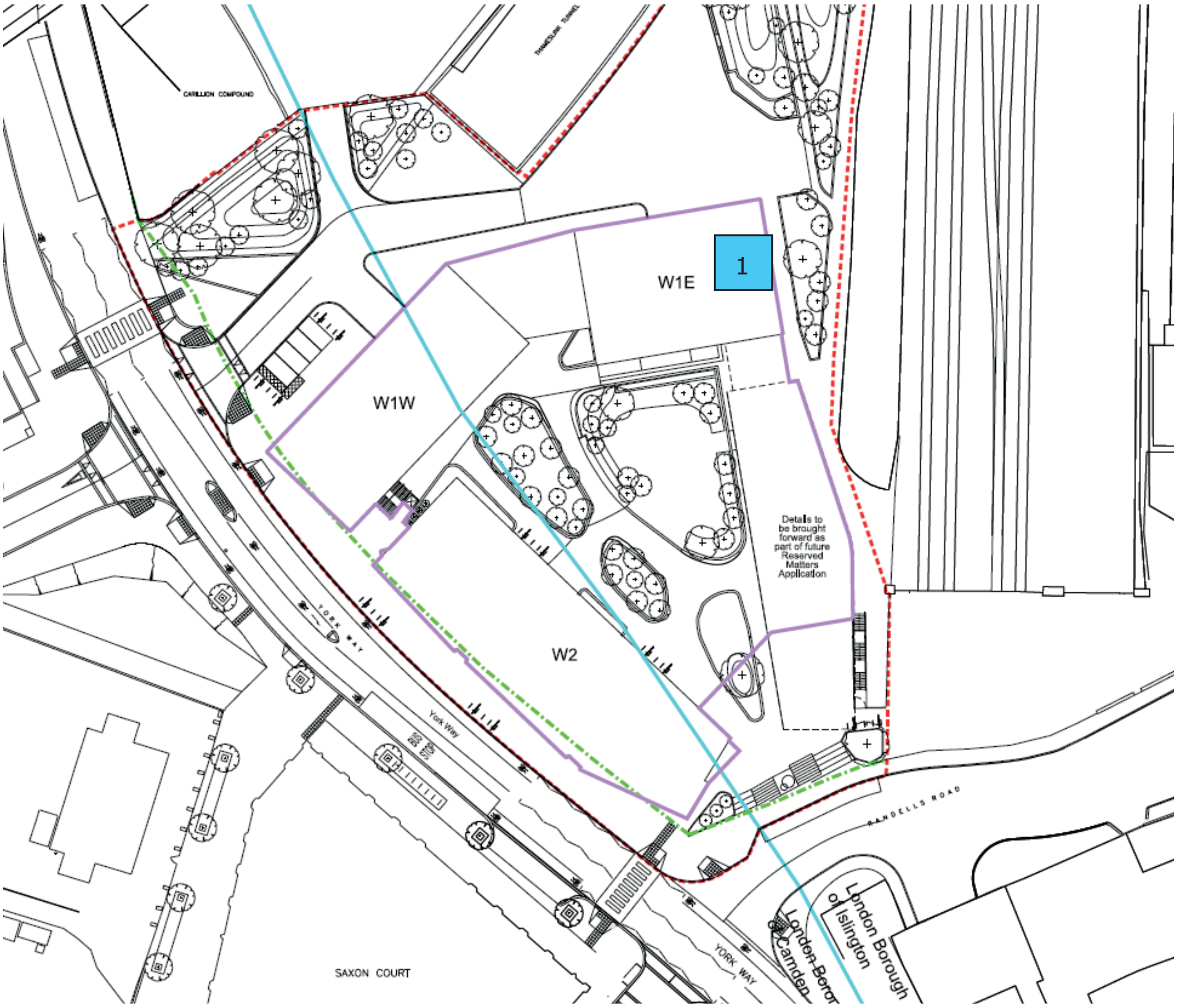

Figure 2 **Vibration measurements position**

5.1 Measurement equipment

The following measurement equipment was used to conduct the vibration survey.

- Svantek SVAN958 'Class 1' Real Time Analyser;
- PCB 393A01 seismic accelerometers;
- Magnetic block and ground spike; and
- Environmental protective case with battery

The 3 axis orthogonal array of accelerometers was securely mounted to the ground using a magnetic block and ground spike. The two horizontal axes were aligned to the railway lines (x,y axes) with the third axis (z) monitoring in the vertical plane.

5.2 Measurements results

Figure 3 presents the measured 1/3 octave band vibration results. These indicate the maximum vibration levels (un-weighted accelerations) on the vertical axis, measured at the vibration monitoring locations, compared to the typical human threshold of perception. Below this level it is generally accepted that most people will be unable to perceive vibration.

Perceptibility thresholds are based upon guidance given in *BS6472:1992.*

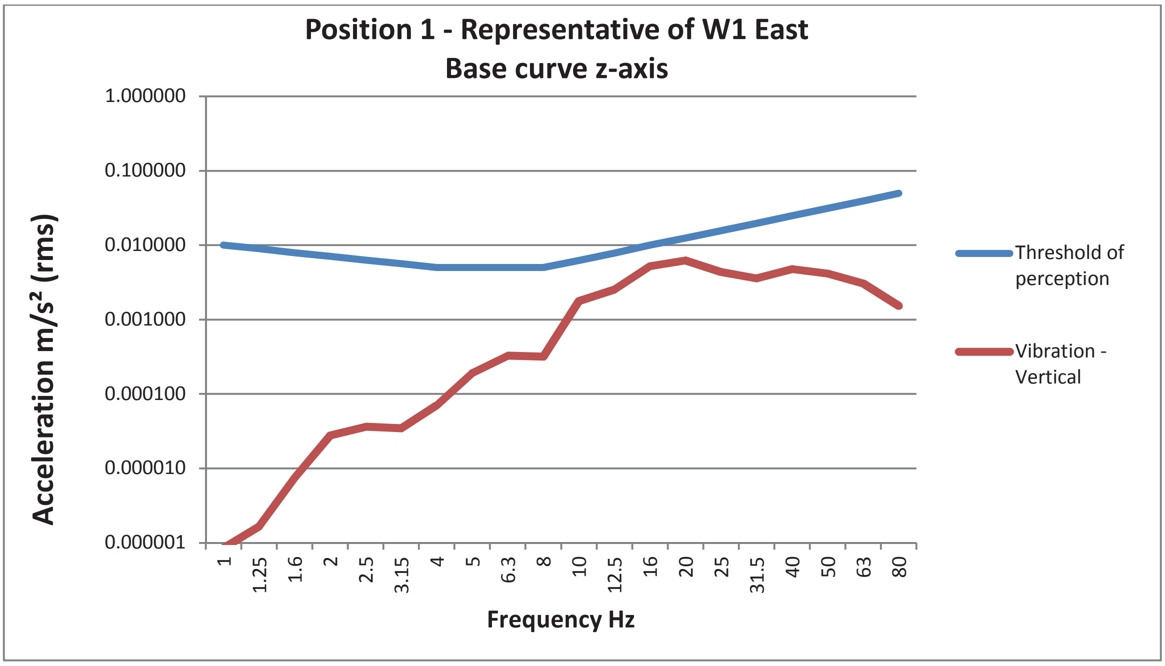

Figure 3 **Vibration measurements results at Position 1 – vertical axis**

5.3 Structureborne noise from ECML

Structure-borne noise is generated as a result of vibration energy caused by a source external to a building entering the structure, typically via the foundations, and transmitted through the building structure.

The vibration energy excites lightweight constructions such as rigidly fixed partitions, suspended ceilings and raised access floors which re-radiate the energy as audible noise. Typically the noise is heard as a low frequency rumble when the sources, in this case trains, pass close to the building.

Structure-borne noise level can be calculated on the basis of the measured acceleration (rms) during a train pass-by, in accordance with the methodology given in the Association of Noise Consultants guidelines[2] and applying corrections following guidance provided in the Transportation Noise Reference Book[3].

Calculations undertaken on the basis of the procedure set out above show that the expected structure-borne noise caused by train pass-by on the ECML inside Building W1 East, which is the closest to the train line, will be in the region of **$L_{Amax,s}$ 30**[4] **dB** at ground level. Subsequently, this is also true for Building W2 which is located further away from both the ECML. This complies with Triangle Outline Planning Permission Condition 29.

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[2] The Association of Noise Consultants: Measurement & Assessment of Groundborne Noise and Vibration, 2nd Edition: 2012

[3] Transportation Noise Reference Book: P.M. Nelson, Butterworth & Co Ltd, 1987

[4] This is assuming worst case coupling losses between the ground and the piles of the proposed buildings and worst case correction for amplifications due to resonance of slabs on columns, as detailed in Chapter 16 of the Transportation Noise Reference Book

6. THAMESLINK CANAL TUNNEL ASSESSMENT

The assessment of the impacts on Building W1 West and Building W1 East, which are the closest buildings to the TCT, required detailed finite element analysis to predict the vibration propagation from the trains once the tunnels will be in operation. Demonstrating compliance for these building will also demonstrate compliance for Building W2 which is further away from the TCT.

The model is the finite-difference time-domain (FDTD) model FINDWAVE®, an industry standard model used for the modelling of railway noise and vibration. FINDWAVE® is also capable of modelling the vibration of railways at grade or in underground tunnels, including the transmission of ground-borne noise from the tunnels to the ground surface and into buildings.

6.1 Assumptions and limitations

The assumptions for the modelling exercise are discussed in detail in the main body of the structureborne noise modelling report which is provided in Appendix A.

For this summary, it is worth noting the modelling has assumed that the high level attenuated track HA-LVT from Sonneville is used within the Canal Tunnels. This is based on Network Rail's commitments with the selection of track form set out in its report "*Thameslink Programme Contract N306 – Canal Tunnels Document Number N306-BBH-RT-400230*". An extract showing the details of the track is provided in Appendix B to this report.

As a result, the modelling predictions are reliant on the installed HA-LVT performing to its nominal performance. The predictions are also based on the building design information provided to date (Design Clip 14b provided in Appendix C). It should be noted that buildings have been modelled with no structural isolation at foundation or floor level.

In addition, it should be noted that there is an inherent uncertainty with the prediction of ground borne noise and vibration which is likely to be ± 5dB.

6.2 Results

The results of the modelling show the following A-weighted maximum (slow time weighting) ($L_{Amax,s}$) noise levels:

Floor	Noise level, dBL_{ASmax}	
	W1 West	W1 East
Podium[1]	36[1]	31
Level 01	33	31
Level 02	30	32
Level 03	28	30
Level 04	26	30
Level 05	26	28
Predicted Structureborne noise at higher levels is below 30dB $L_{Amax,s}$.		

[1] While the maximum noise level reported at Podium level of Building W1 West is 36dB $L_{Amax,s}$ we note that this is as a result of a minor exceedance localised in a very small area at podium level, at the location shown in the plot below (**Figure 4**). On average, the noise level inside partitioned rooms, will be below 35 dB LAmax,s This minor exceedance is therefore considered not be significant.

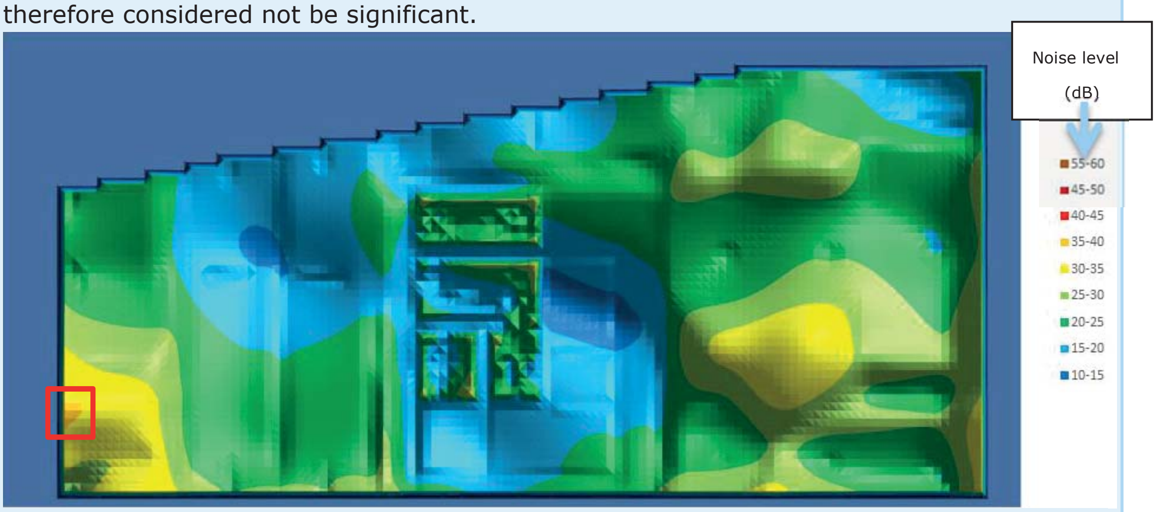

Figure 4 Graphic plot showing pseudo noise level (dB) due to floor vibration for W1 West building at Podium level

Table 1 Predicted structureborne noise level in Building W1 West and W East and colour plot showing Podium Level for Building W1 West

6.3 Conclusions

The result of the modelling work show that the expected structureborne noise level arising from TCT and ECML inside Buildings W1 East and W1 West will be below 35dB $L_{Amax,s}$ without the need of building isolation. In turn, structureborne noise affecting Building W2 will be lower as it is further away from both lines. This is dependent on the HA-LVT track performing to its nominal specification.

It should also be noted that the buildings will benefit from further attenuation thanks to the added floor mass introduced by the fit-out (up to 3 dB), which is to include a screed floor solution. Therefore, even when considering the worst case uncertainty of +5dB, with the full fit-out the internal structure borne noise levels will still comply with Planning Condition 29 throughout Building W1 East and Building W1 West (with the exception of a possible minor exceedance at Podium level as shown in Figure 4, which is not considered to be significant).

APPENDIX A – STRUCTUREBORNE NOISE MODELLING REPORT

Ramboll UK Limited

King's Cross Central: Triangle Site
Modelling of Groundborne Noise and Vibration

Building W1

Report

Issue 3 Revision 1 13th November 2015

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APPENDIX II The FINDWAVE® Model

1. INTRODUCTION

Rupert Taylor Ltd was instructed by Ramboll UK Ltd to carry out a study of the likely level of groundborne noise in the proposed development of W Zone at King's Cross, due to the operation of the railway tunnels known as the "Canal Tunnels" on the King's Cross Railway lands which will form part of the extended Thameslink network. The study was carried out by means of numerical modelling.

This report presents the results of modelling building W1-West and W1-East originally presented in Issue 2 of this report, and updated in accordance with the revised design in "Design Clip 14b" dated 28/08/2015.

2. METHODOLOGY

The predictions were carried out using the Rupert Taylor Finite Difference Time Domain model *FINDWAVE®*.

FINDWAVE® is a fully three-dimensional finite-difference time-domain model specifically developed for modelling vibration and groundborne noise from underground railways. It has been used on many projects around the world, including Crossrail, Thameslink 2000, Jubilee Line Extension, Channel Tunnel Rail Link and Docklands Light Railway in London, Malmö Citytunnel and Västlänken in Sweden, Singapore Central Line, Parramatta rail link in Sydney, Mostoles-Navalcarnero in Madrid, Metro North in Dublin, and a large number of other projects.

The study involved the creation of a three-dimensional *FINDWAVE®* model of part of the proposed building and predicting and vibration, and thereby groundborne noise, in the buildings.

The model used

FINDWAVE® is a finite difference time-domain numerical model for computing the propagation of waves in elastic media. Full details of the model are given in Appendix II. The railway implementation of *FINDWAVE®* includes the train as a stack of damped masses and springs representing the rail vehicle. The excitation is provided from an input file containing an assumed vertical rail head profile, together with the gravitational effect of the rolling train. The train moves in the model and the location of the contact patch for each wheel is constantly advancing (re-entering the model at the front when it goes beyond the end). The interaction between the contact patch and the rail is transferred to the relevant fixed rail elements using polynomial interpolation.

The model predicts, in the time domain, the dynamic behaviour of the track and structure supporting the train, and the medium surrounding it, e.g. soil or air, together with structures below or above ground level. The structures concerned are represented as cells in a 3-dimensional orthogonal grid, each cell being assigned density, Lamé constants and loss factor.

The models have a basic cell size of 300mm, varied locally to suit the characteristics of elements in the model. A basic time step of 1/131072 seconds was used, increasing according to the courant number of specific cells. The model was run for a time period of 1 second. Output from the model consists of time series of the velocity of relevant parts of the structure, which are subjected to frequency transformation and expressed as 'A-weighted' overall levels and 1/3 octave band spectra.

The building models were created based on the drawings listed in Appendix 1 up to the eleventh floor. An isometric view of the models is shown in Figure 1. Example cross sections through the models are shown in Figure 2, and horizontal sections through the models at track level is shown in Figure 4.

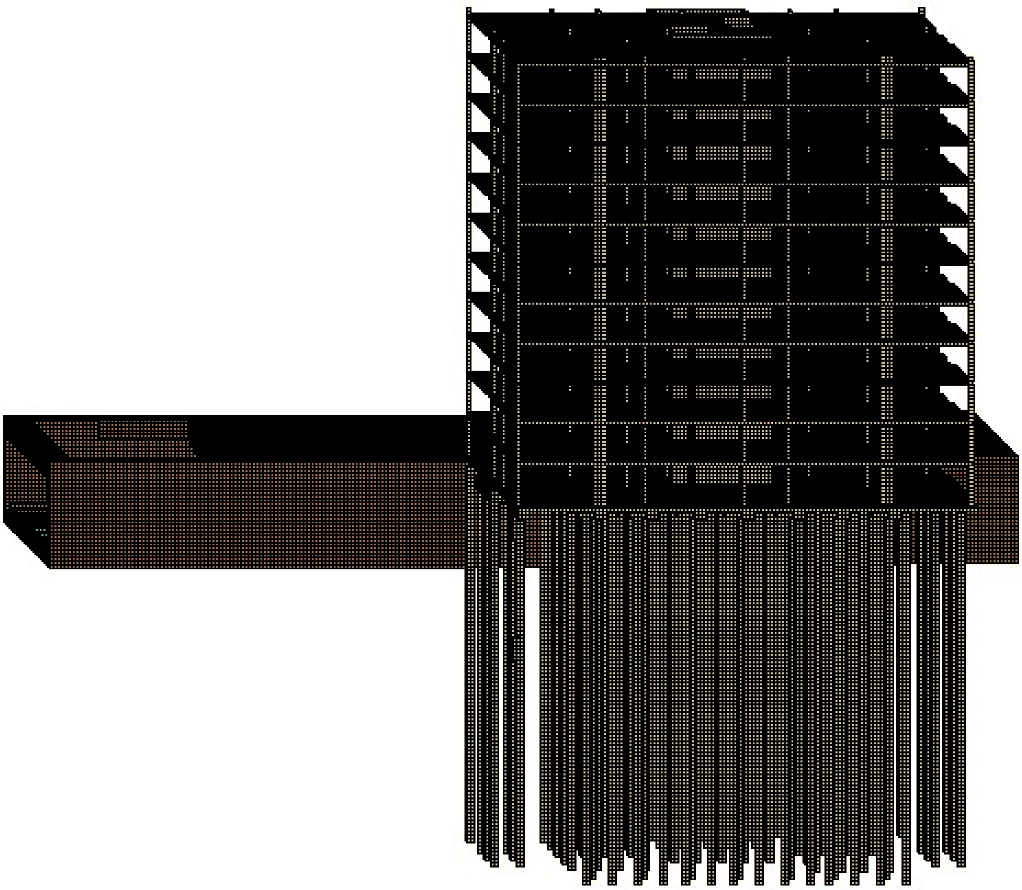


Figure 1 Isometric view of the model of the West Block of Building W1 (soil removed for clarity)

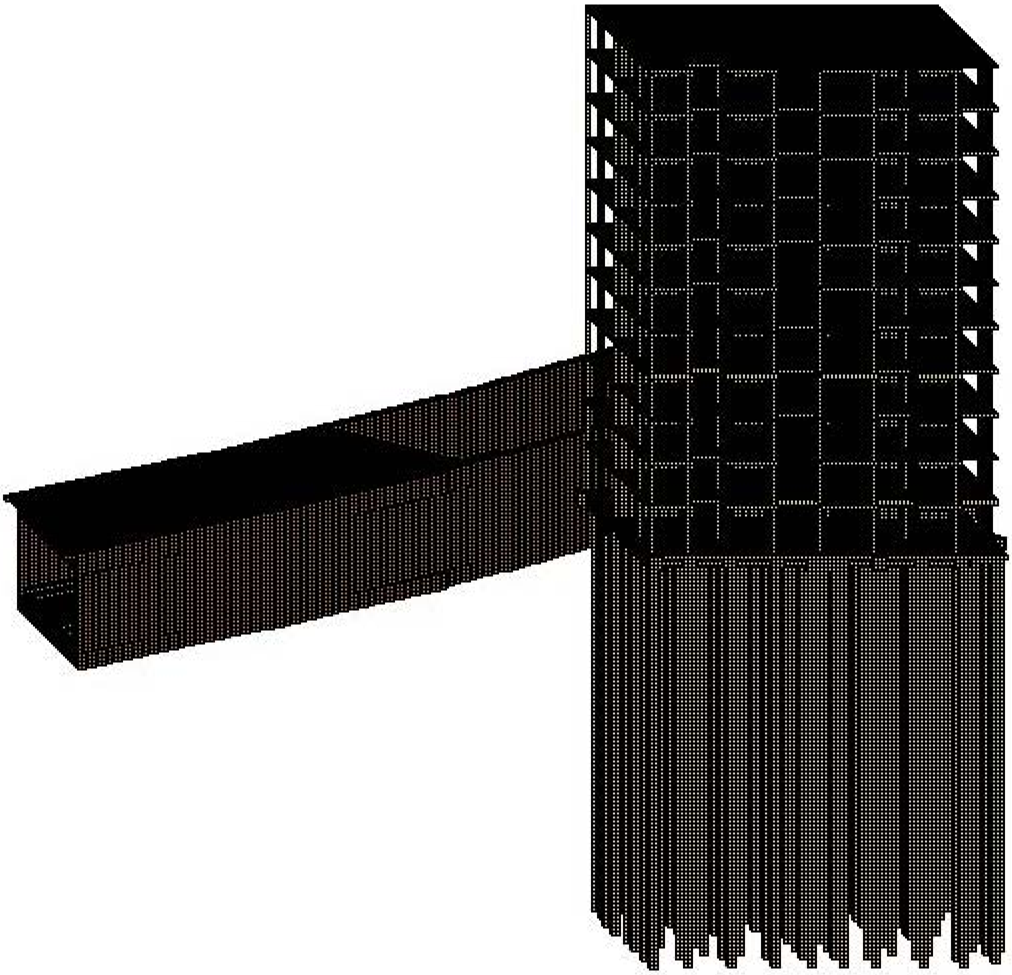


Figure 2 Isometric view of the model of the East Block of Building W1 (soil removed for clarity)

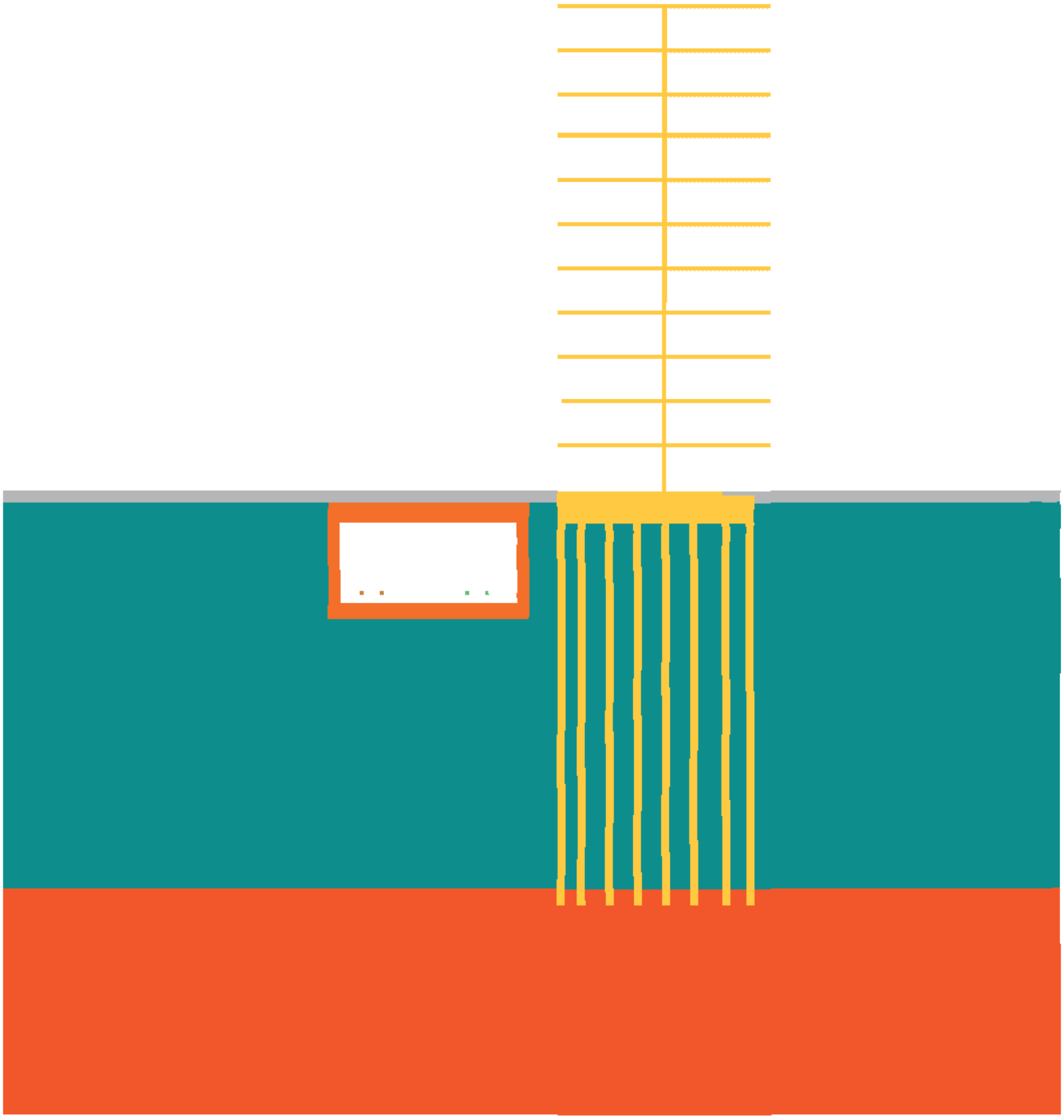
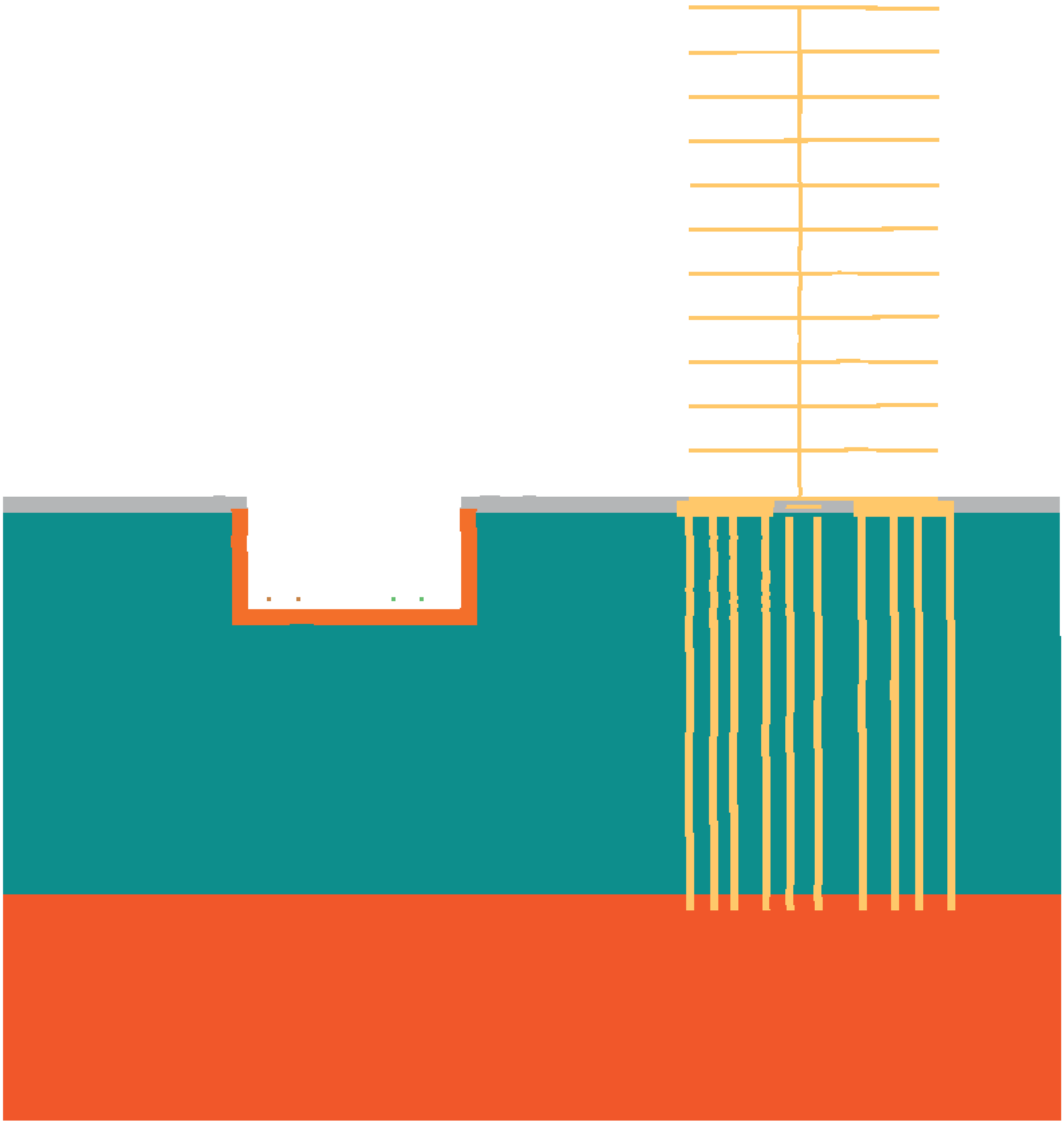


Figure 3 Section through the model of the West Block of Building W1 including the railway tunnel (see table on page 11 for colour code)



East Block

Figure 4 Section through the model of the East Block of Building W1 including the railway (see table on page 11 for colour code)

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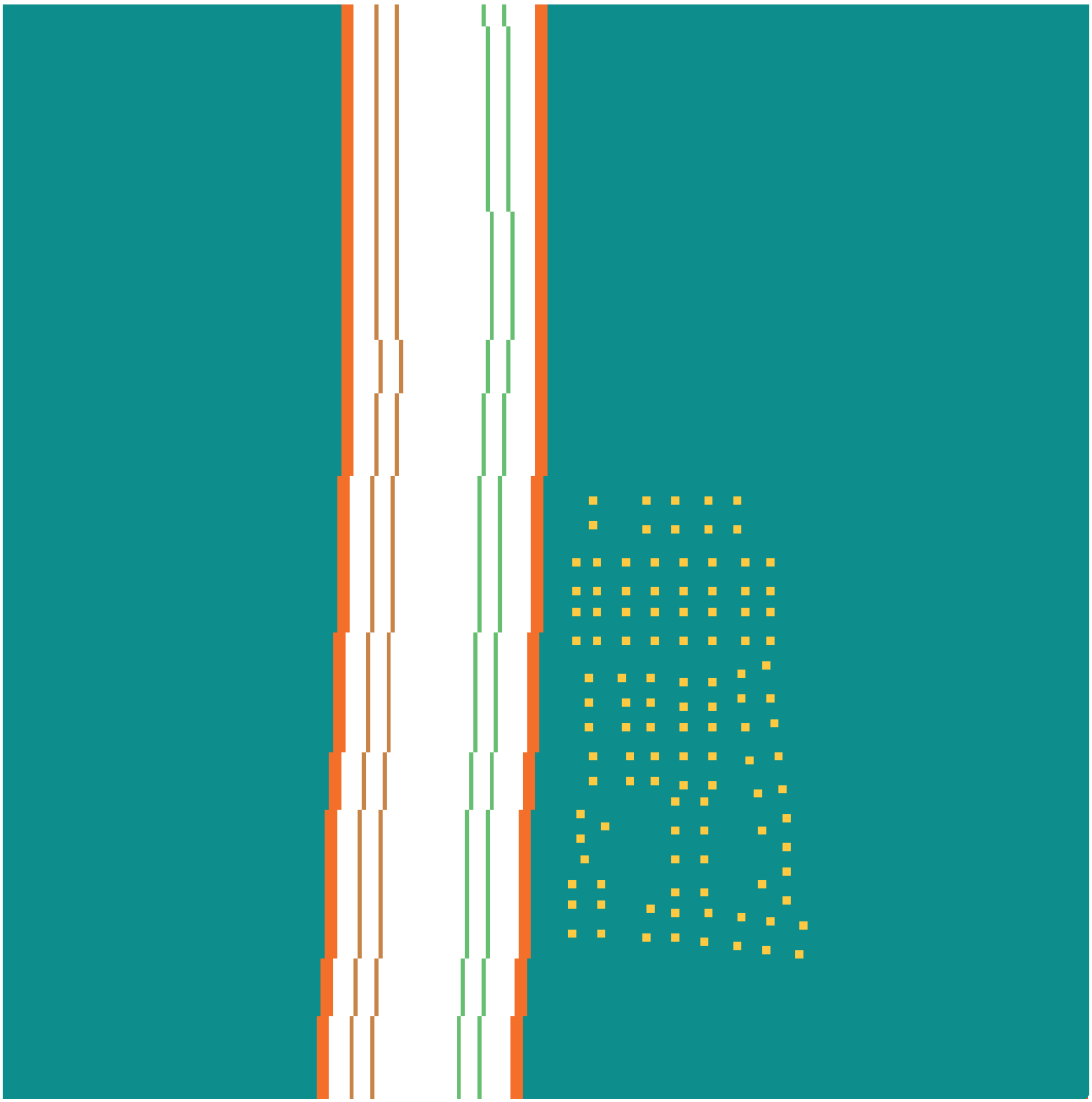

Figure 5 Horizontal section through the model of the West Block of Building W1 at track level, showing tunnel, track, soil and horizontal section through piled foundations

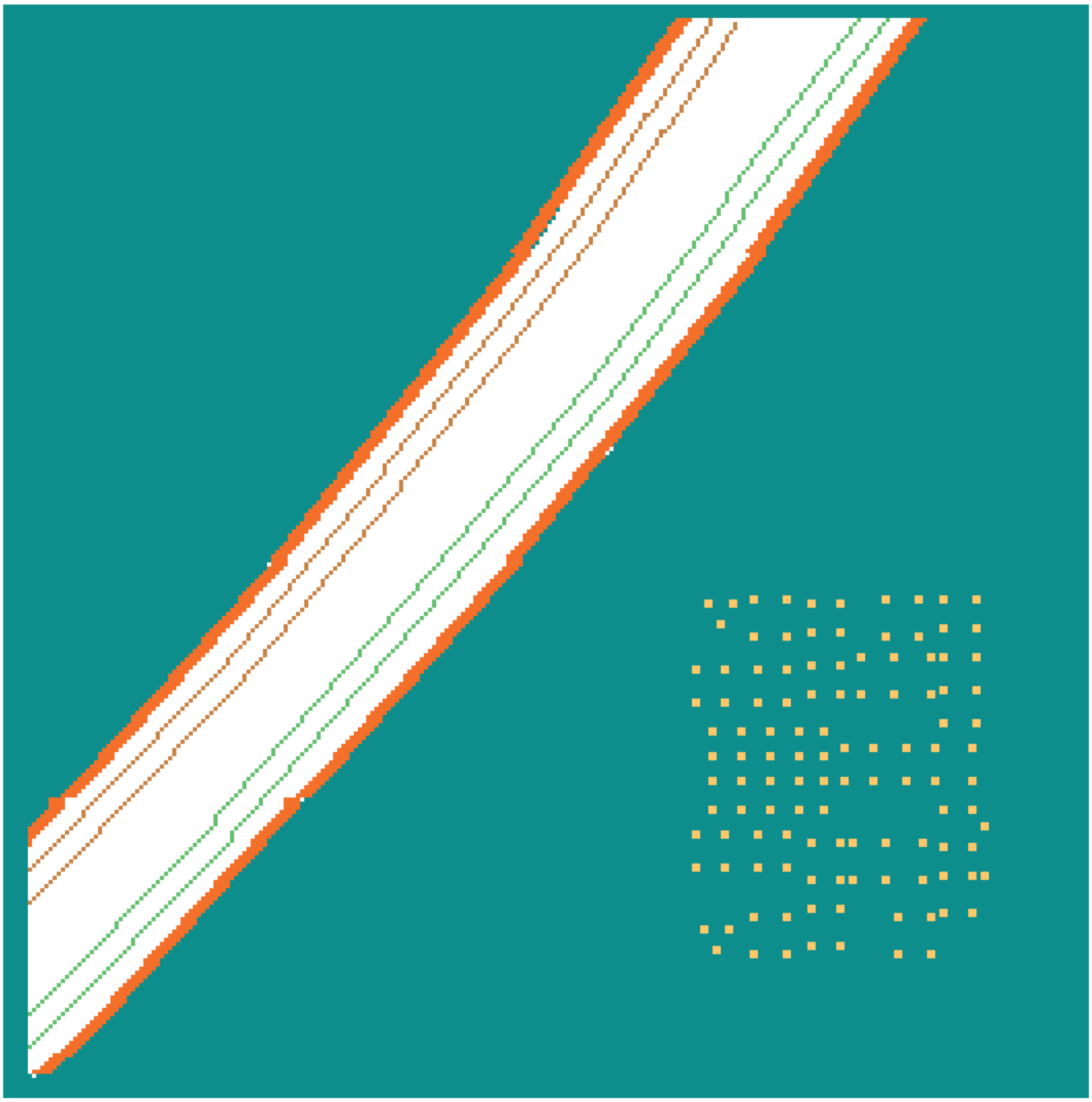

Figure 6 Horizontal section through the model of the East Block of Building W1 at track level, showing tunnel, track, soil and horizontal section through piled foundations

3. MODELLING ASSUMPTIONS USED

Rolling Stock

The following information has been used, being the characteristics of current Class 319 vehicles being operated on the Thameslink route. It should be noted that new rolling stock is likely to be introduced in the future which has not been modelled. The difference between the effect of present and future stock is likely to be small.

Vehicle mass per wheel	4406	kg
Vehicle secondary suspension stiffness	0.1175	MN/m
Secondary suspension damping	11651	Ns/m
Sprung mass of bogie per wheel	1250	kg
Stiffness of primary suspension	0.9	MN/m
Primary suspension damping	15	kNs/m
Unsprung mass per wheel	900	kg
Hertzian contact stiffness	1.2	GN/m

The axle spacing is 0m, 2.6m, 14.137m and 16.737 with a vehicle length of 27m.

The train speed assumed was 50 km/h.

Track

The rails were assumed to be CEN 60. The track support system was assumed to be Sonneville High Attenuation LVT.

Wheel/rail roughness

The combined wheel/rail roughness assumption used is plotted in figure 5 and is a 1/3 octave band spectrum, with the r.m.s. amplitude in the band centred on a wavelength of 2m being 30dB re 1 micron, decreasing with wavelength at the rate of 15 dB per decade. This assumption is representative of the combined wheel/rail roughness spectrum found on mass transit systems. It was derived following studies of the wheel and rail roughness measurements in the Rupert Taylor library, which were made on the District and Circle Line at the old Westminster and Circle Line Station, in the Channel Tunnel, in the Liverpool Loop, on Stockaryd-Lidnas and Helsingborg lines in Sweden and on wheelsets at the Ealing Common Depot of London Underground and on class 307 wheels at Birkenhead North Depot. There are, however, systems in existence which achieve a roughness spectrum of smaller amplitude, usually through a programme of pre-emptive rail grinding, or by the existence of favourable track characteristics.

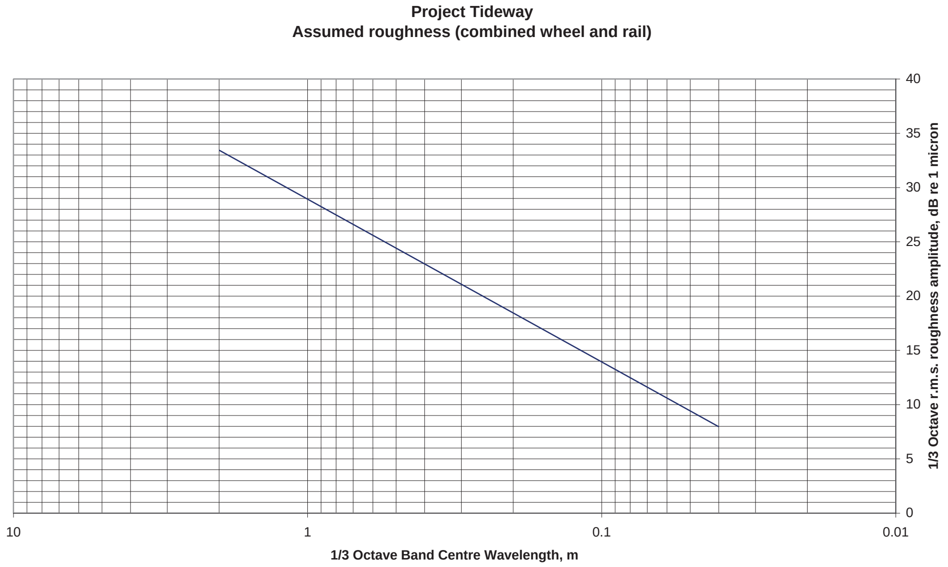

Figure 7 Combined wheel/rail roughness spectrum

Material characteristics

The following assumptions concerning soil characteristics were used in the models, taken from Rupert Taylor Ltd library data for sites in London.

The properties assigned to the materials modelled were as follows. The modulus assumptions are relevant to the extremely small strains involved in groundborne noise and vibration, and are not necessarily the same as those used for civil engineering purposes. The property D is the compressive modulus, given by

$$D=2G(1-\sigma)/(1-2\sigma)$$

where σ is Poisson's ratio and G is shear Modulus.

	Material	Shear Modulus, *Gmax*, GPa	Compression Modulus, *D*, GPa	Density, ρ kg/m^3	Loss factor η
🟨	Concrete	11.64	31.11	2400	0.05
🟥	Concrete	11.64	31.11	2400	0.05
⬜	Made Ground	0.068	0.267	1500	0.05
🟦	London Clay	0.735	4.41	1700	0.05
🟫	Lambeth Group	0.580	5.904	2100	0.03

Table of properties of materials in the model

4. RESULTS

Results are presented in terms of the modelled vertical vibration velocity in the floor slab of each floor. As the detailed design of the proposed building, currently at stage 3, is not yet available making direct output of sound pressure in the rooms impractical, groundborne noise in the rooms of the building has been predicted using the well-established rule-of-thumb[1] that relates vibration velocity to re-radiated structure-borne sound, namely L_p=L_v-27 dB, where L_v is the vertical vibration velocity of the slab in dB re 1 nanometre/second, and L_p is the sound pressure level in a room constructed upon it. This result is referred to as "pseudo noise level". The effect of detailed design cannot be known until it is available.

The overall A-weighted pseudo noise level is presented as colour-coded contour plots on each floor level in Figures 5 to 27 (odd numbers). Spectra at the locations of the highest A-weighted levels occurring in on each residential floor are plotted in Figures 6 to 28 (even numbers). The sound level in each room will be determined not by the worst case level but by the logarithmic average over the relevant floor area. The results are L_{ASmax} levels, and the levels on each floor averaged over the individual residential rooms are

West Block

Podium Level	36 dB L_{ASmax}
Level 01	33 dB L_{ASmax}
Level 02	30 dB L_{ASmax}
Level 03	28 dB L_{ASmax}
Level 04	26 dB L_{ASmax}
Level 05	26 dB L_{ASmax}
Level 06	27 dB L_{ASmax}
Level 07	26 dB L_{ASmax}
Level 08	24 dB L_{ASmax}
Level 09	23 dB L_{ASmax}
Level 10	27 dB L_{ASmax}
Level 11	26 dB L_{ASmax}

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[1] Association of Noise Consultants, Measurement and Assessment of Groundborne Noise and Vibration, Second Edition, 2012

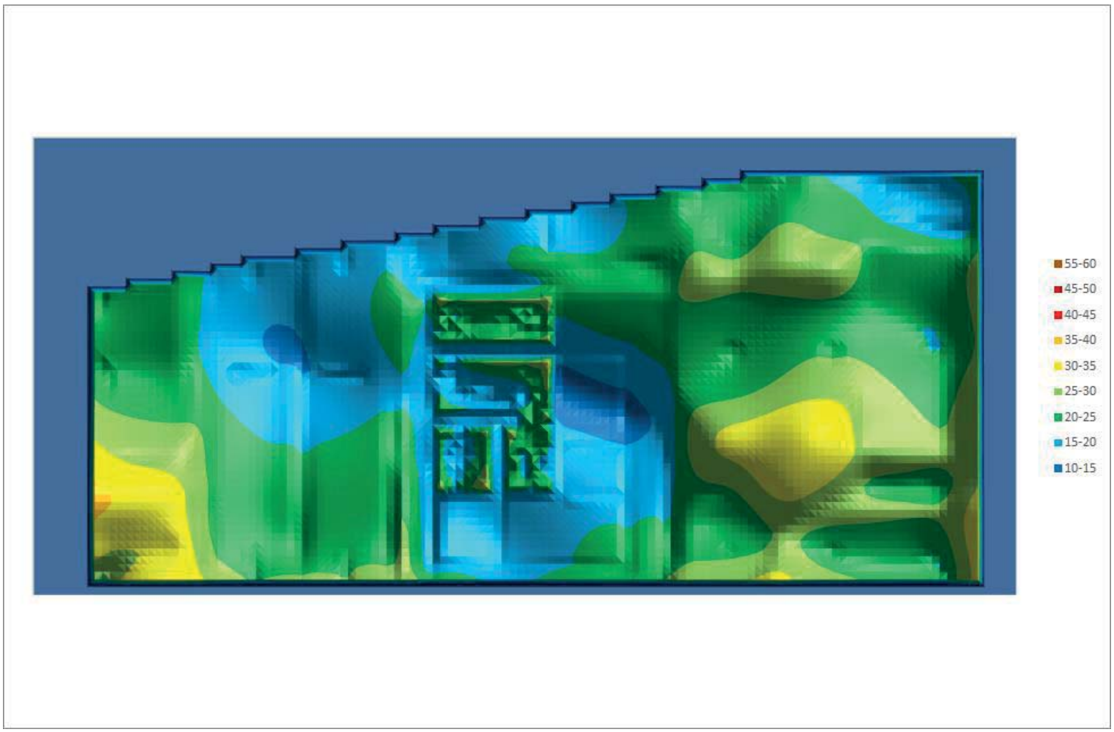


Figure 8 Predicted levels of groundborne noise – Podium Level - West Block - see key to the right of the figure for maximum levels of sound (L_{ASmax}) corresponding to each colour zone in the figure.

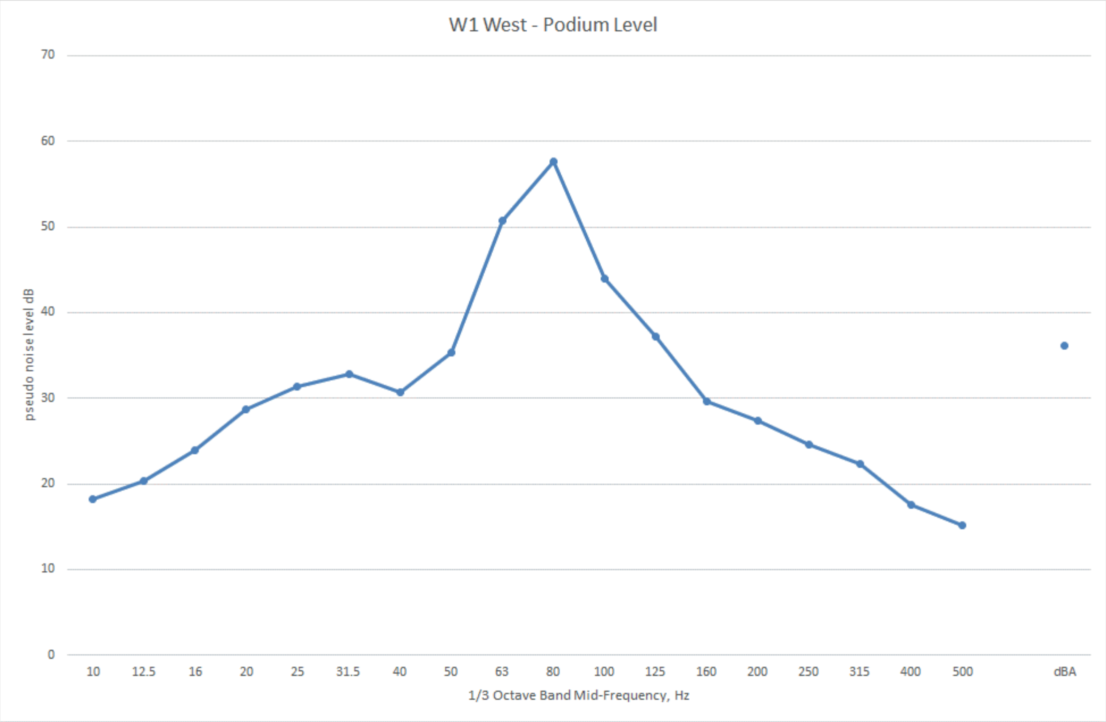


Figure 9 Spectrum for worst case location in Figure 8 – Podium Level - West Block

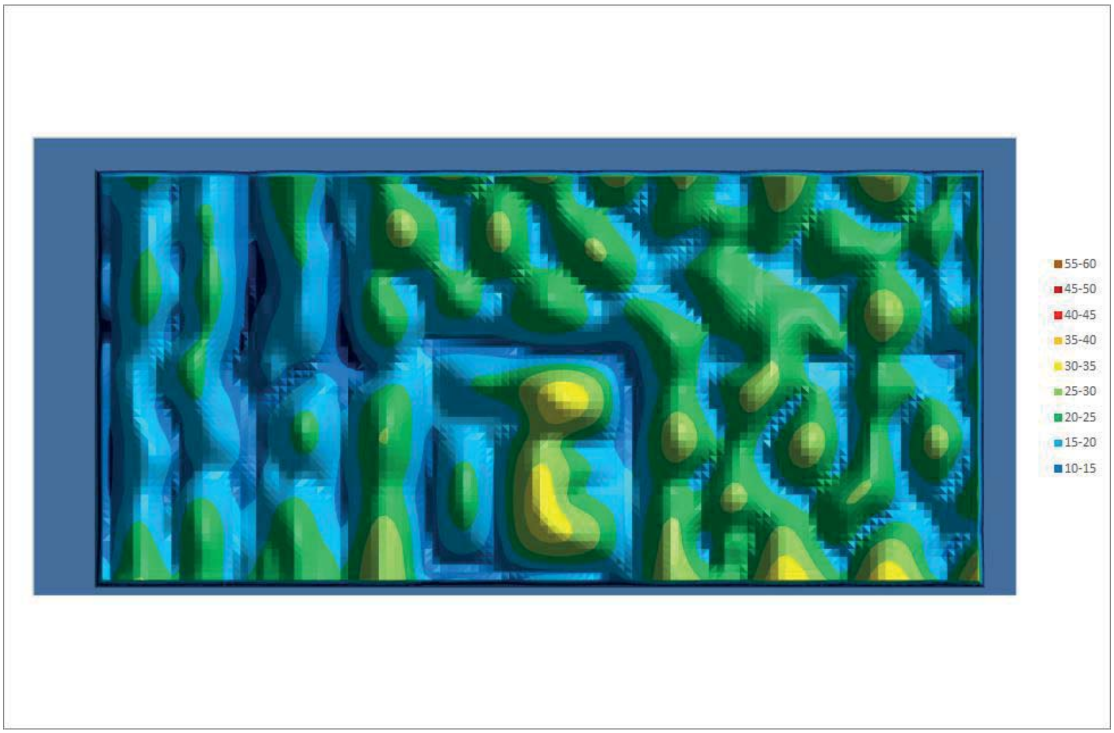


Figure 10 Predicted levels of groundborne noise – Level 01 - West Block

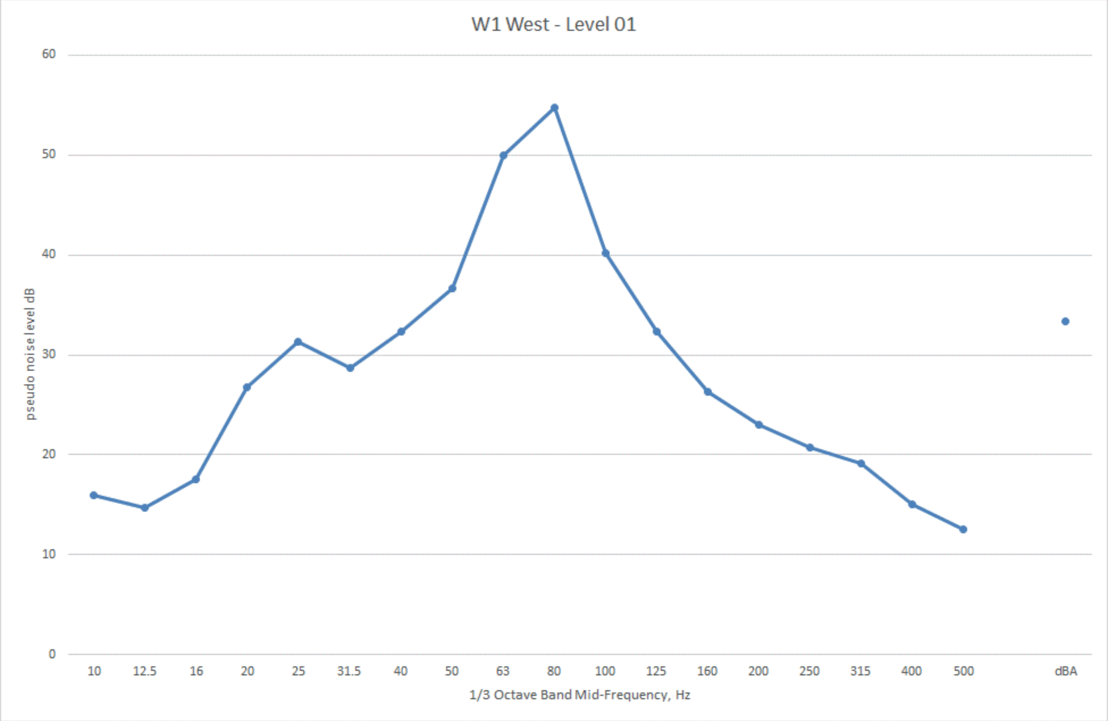


Figure 11 Spectrum for worst case location in Figure 10 – Level 01 - West Block

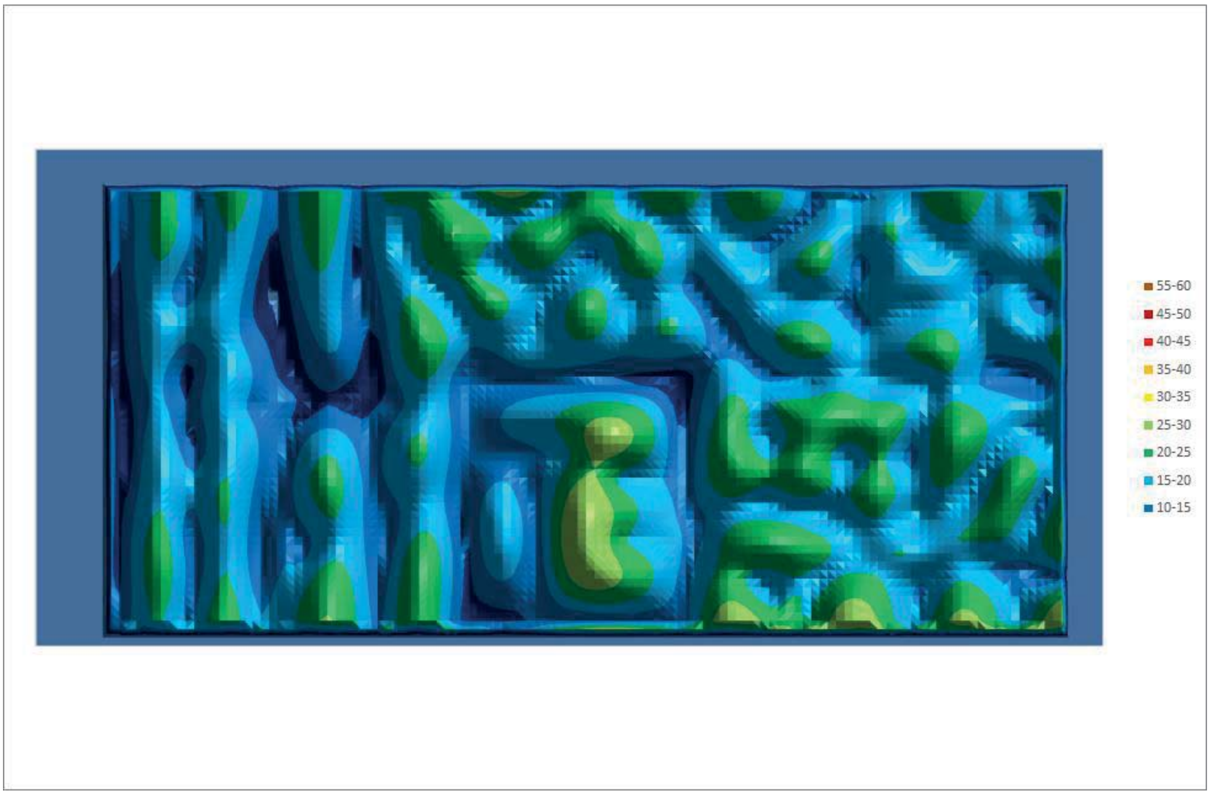


Figure 12 Predicted levels of groundborne noise – Level 02 - West Block

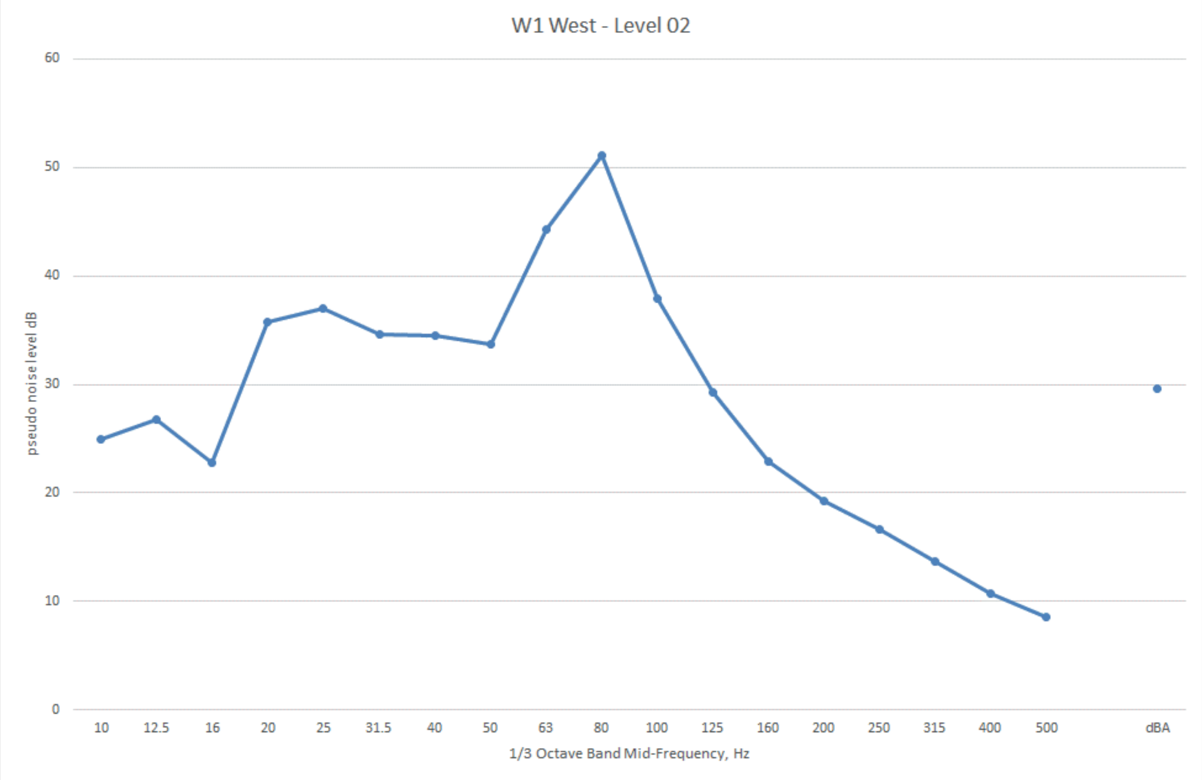


Figure 13 Spectrum for worst case location in figure 12 – Level 02- West Block

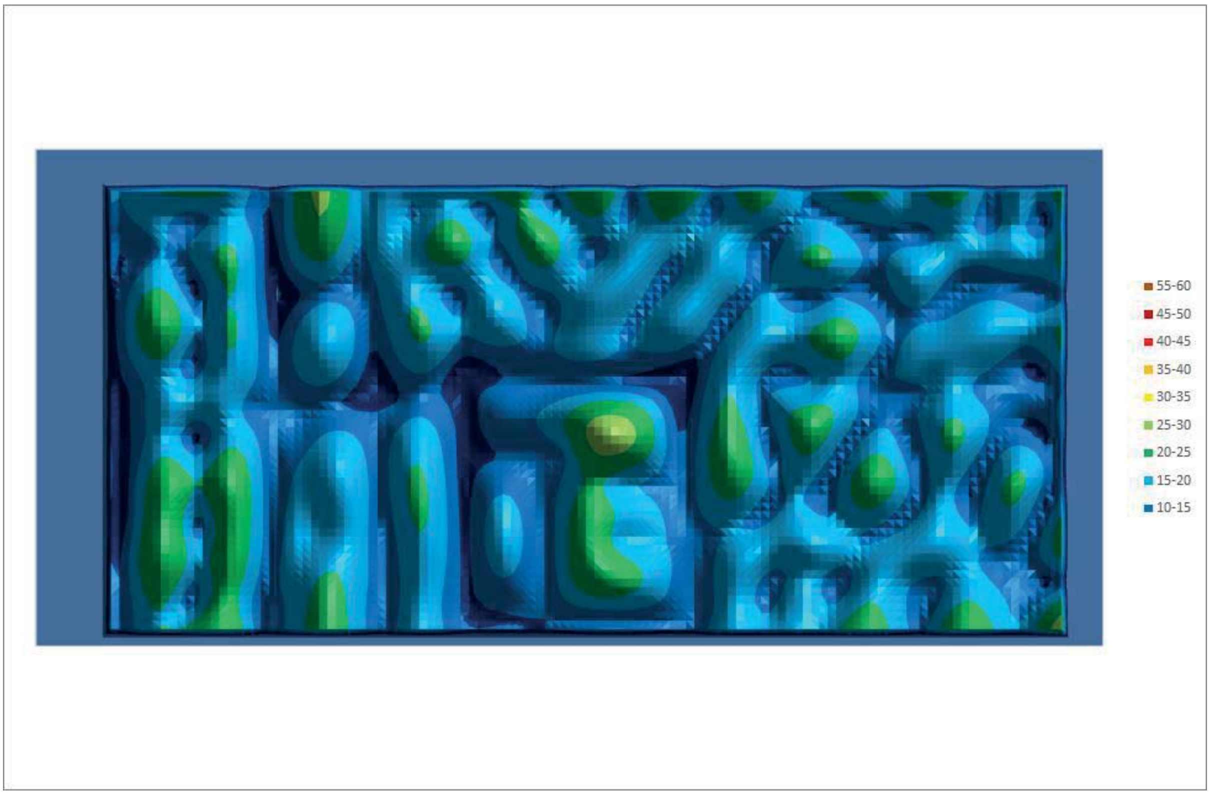


Figure 14 Predicted levels of groundborne noise – Level 03 - West Block

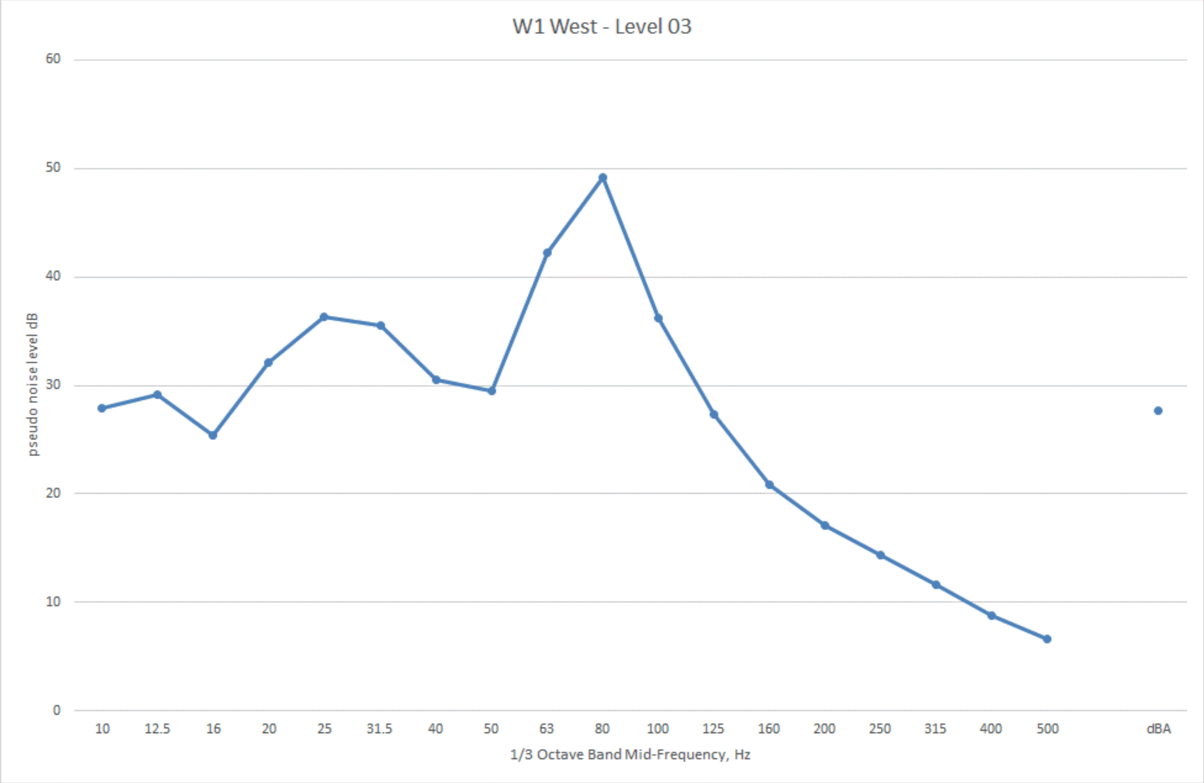


Figure 15 Spectrum for worst case location in figure 14 – Level 03- West Block

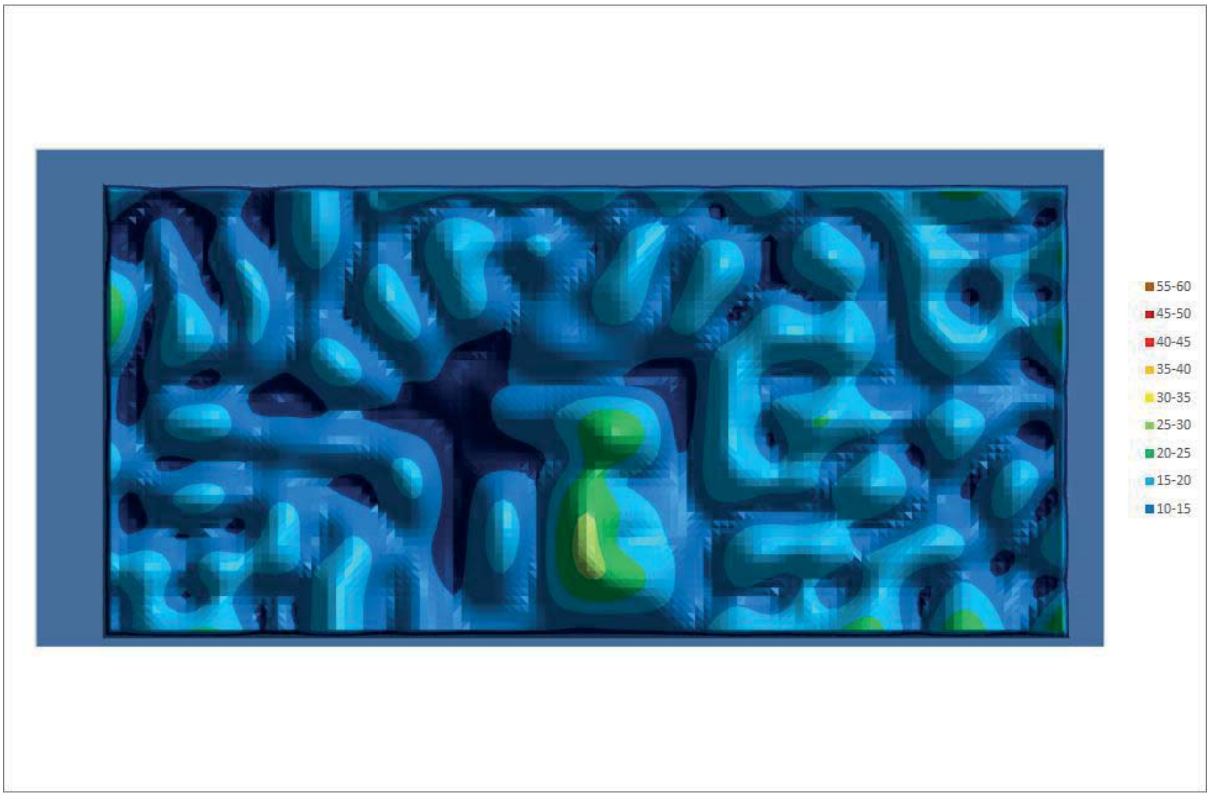


Figure 16 Predicted levels of groundborne noise – Level 04 - West Block

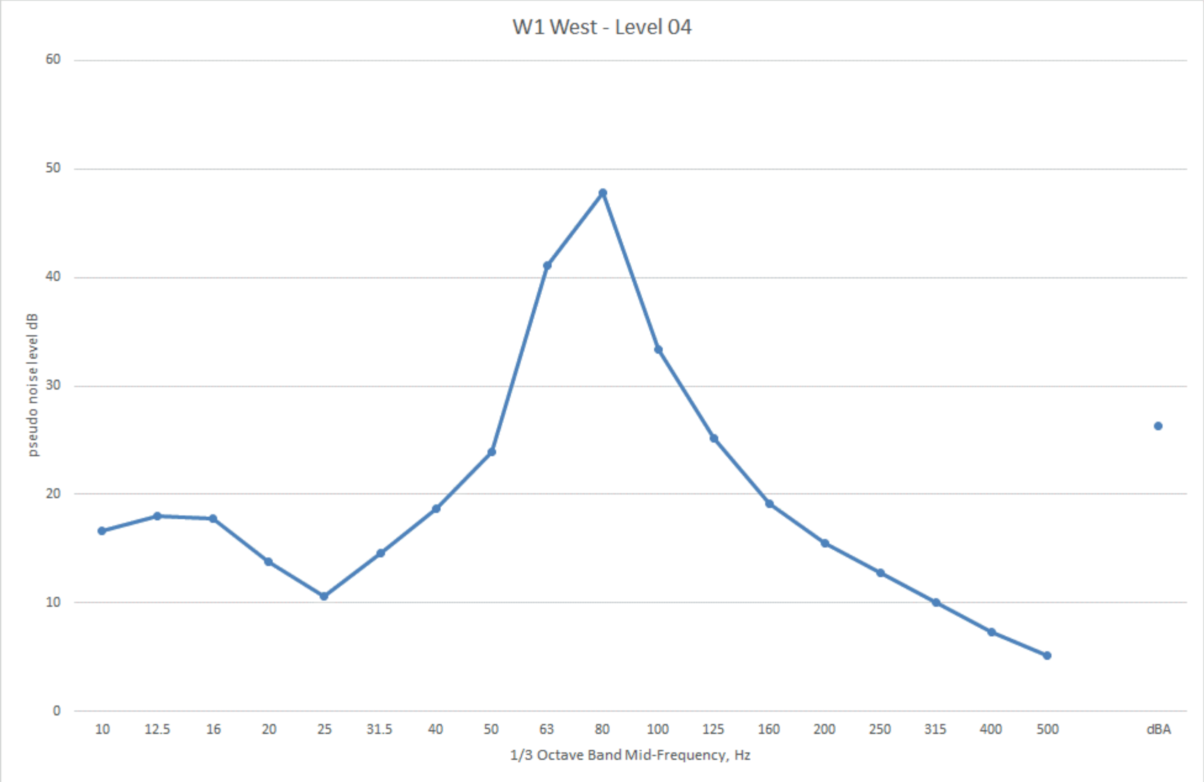


Figure 17 Spectrum for worst case location in figure 16 – Level 04- West Block

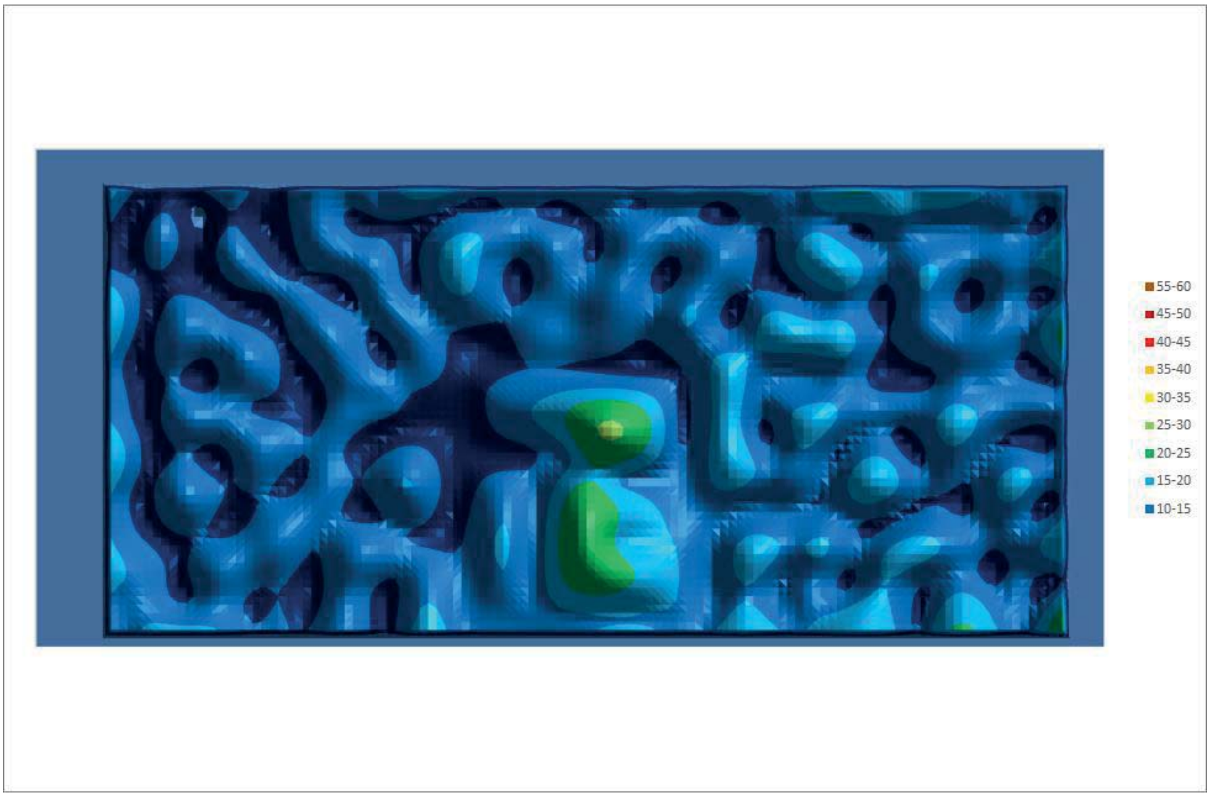


Figure 18 Predicted levels of groundborne noise – Level 05 - West Block

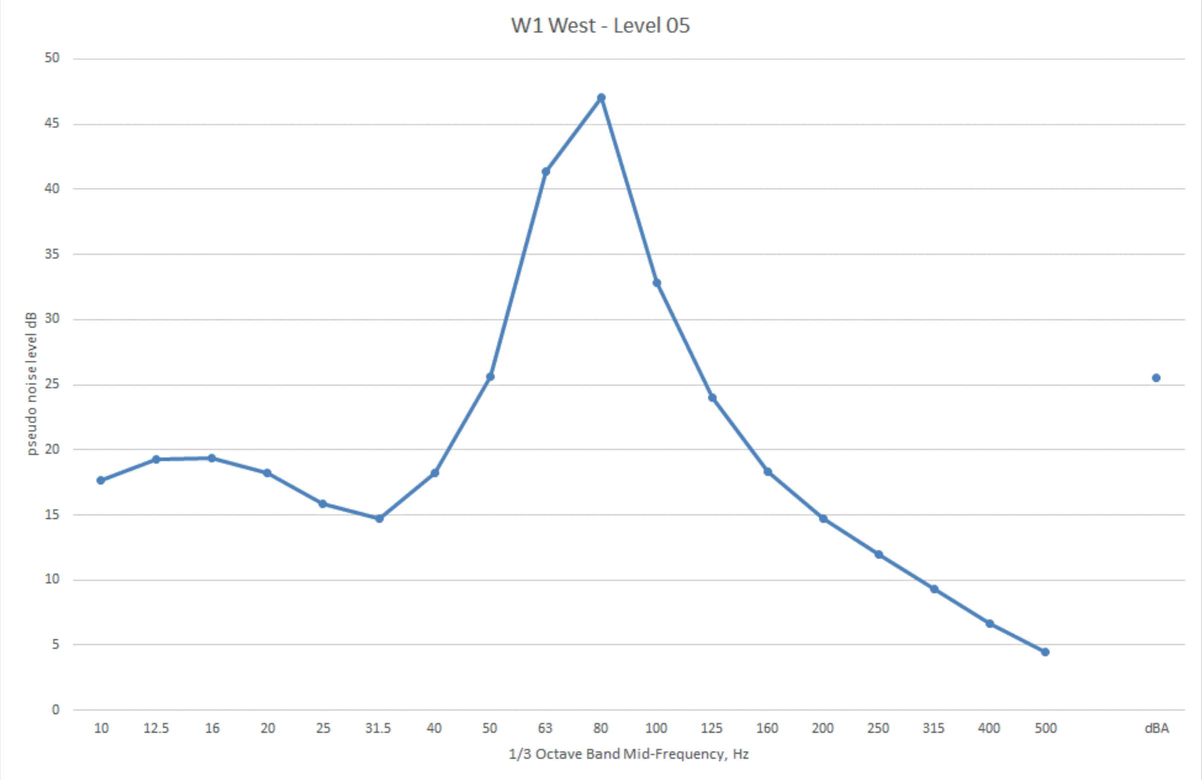


Figure 19 Spectrum for worst case location in Figure 18 – Level 05- West Block

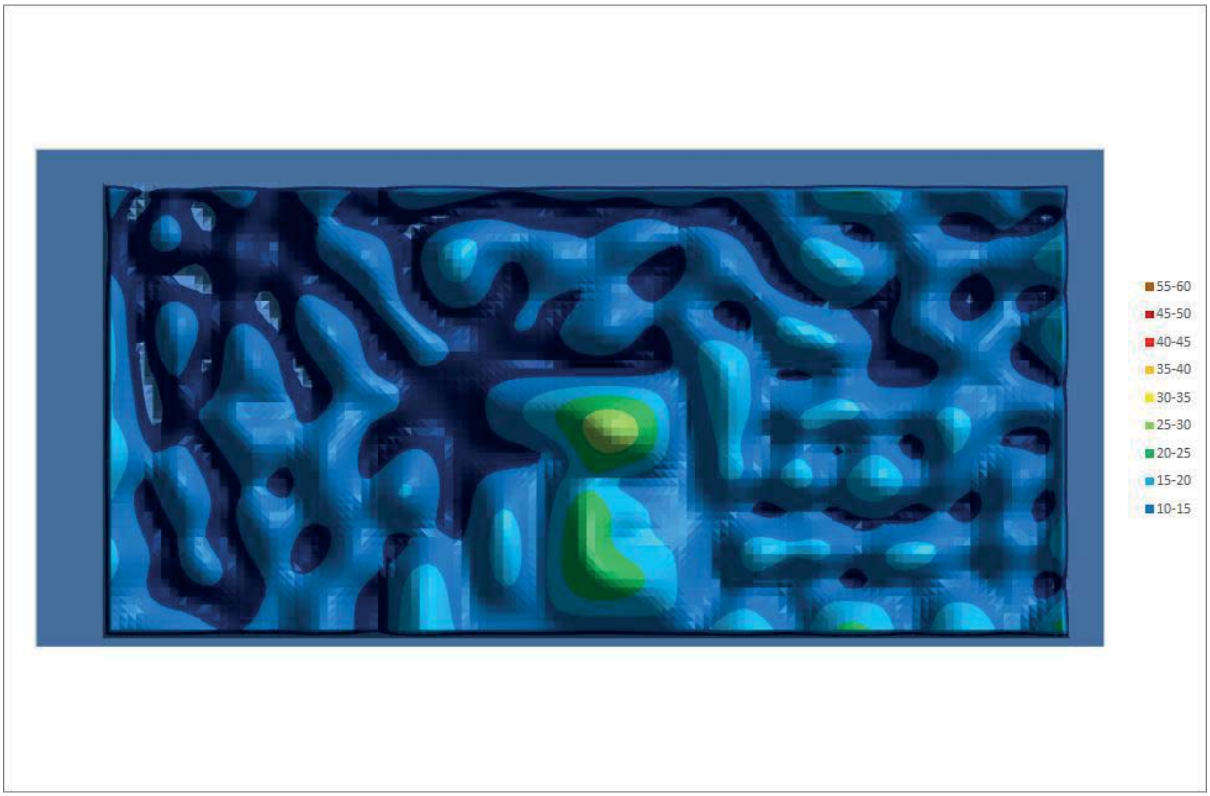


Figure 20 Predicted levels of groundborne noise – Level 06 - West Block

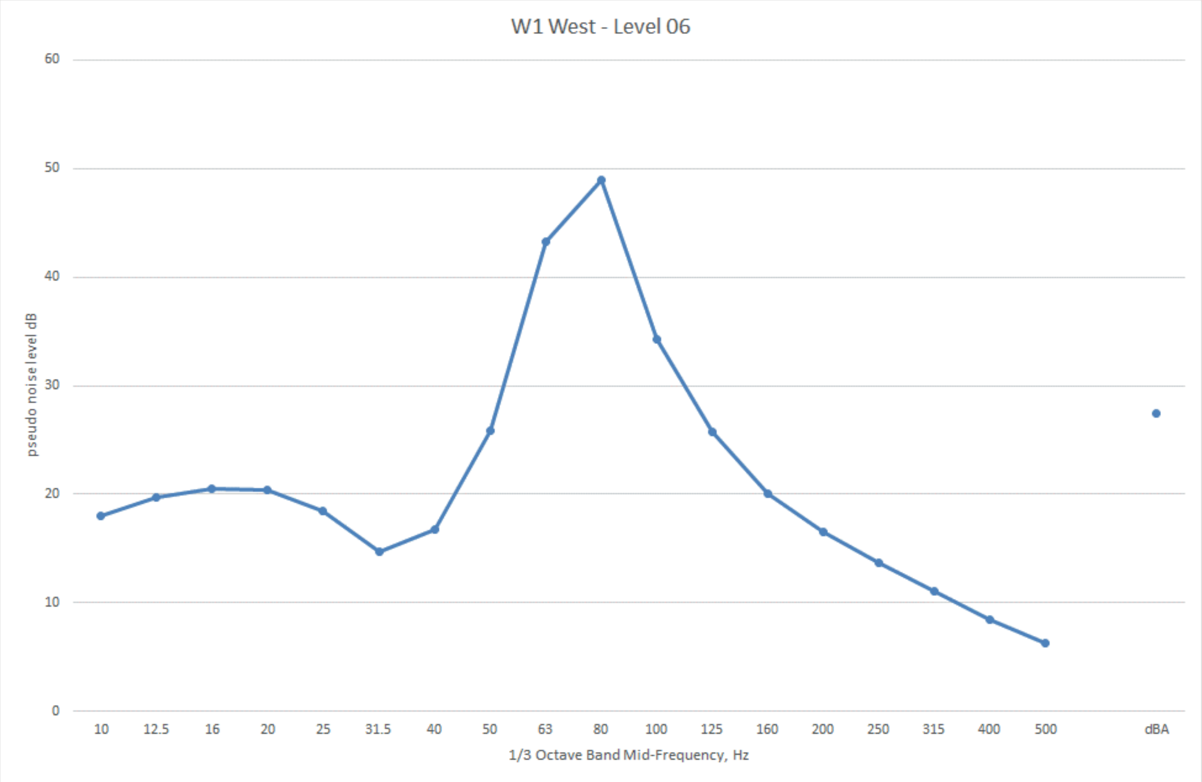


Figure 21 Spectrum for worst case location in Figure 20 – Level 06- West Block

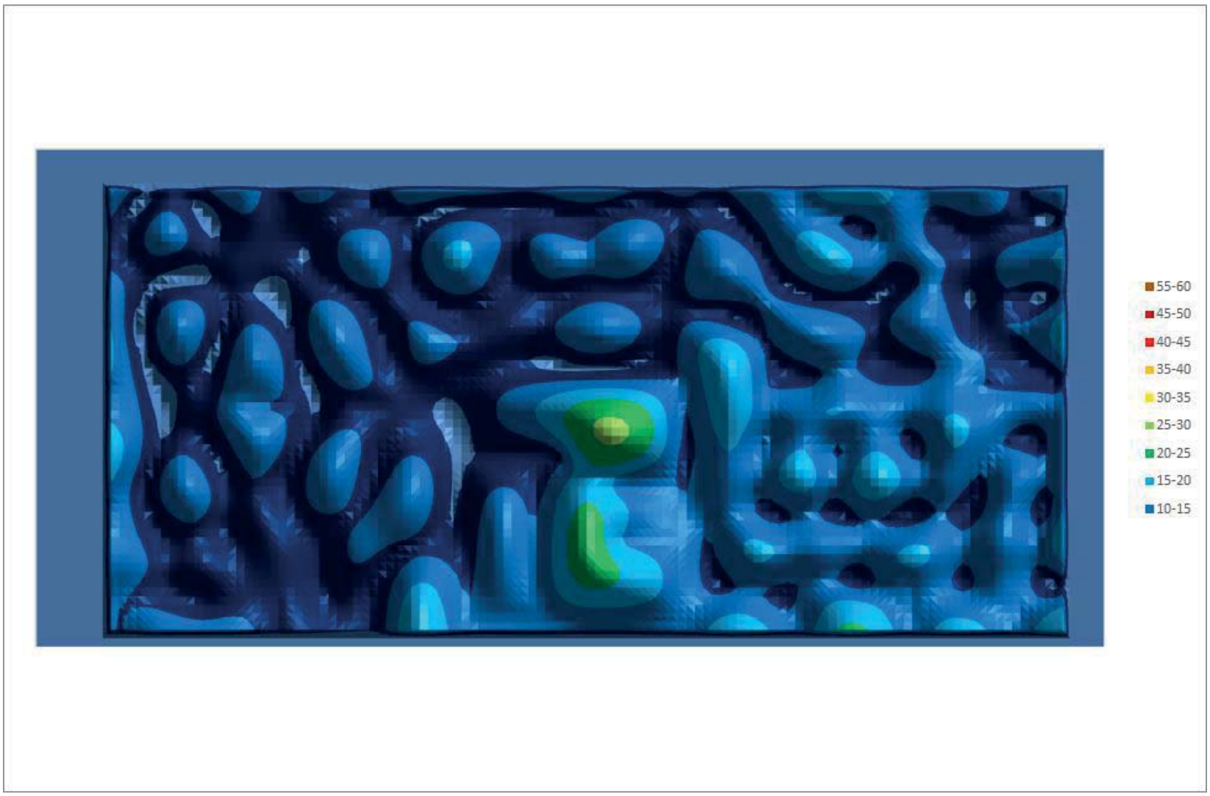


Figure 22 Predicted levels of groundborne noise – Level 07 - West Block

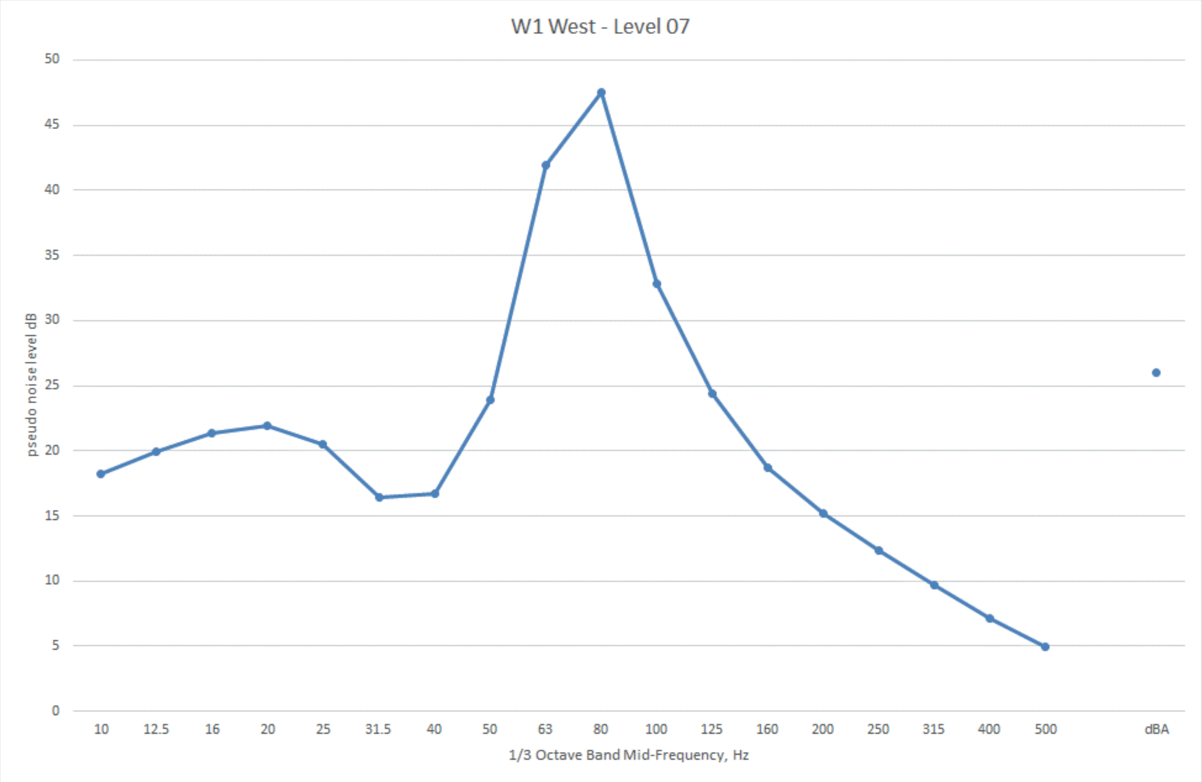


Figure 23 Spectrum for worst case location in Figure 22 – Level 07- West Block

Figure 24 Predicted levels of groundborne noise – Level 08 - West Block

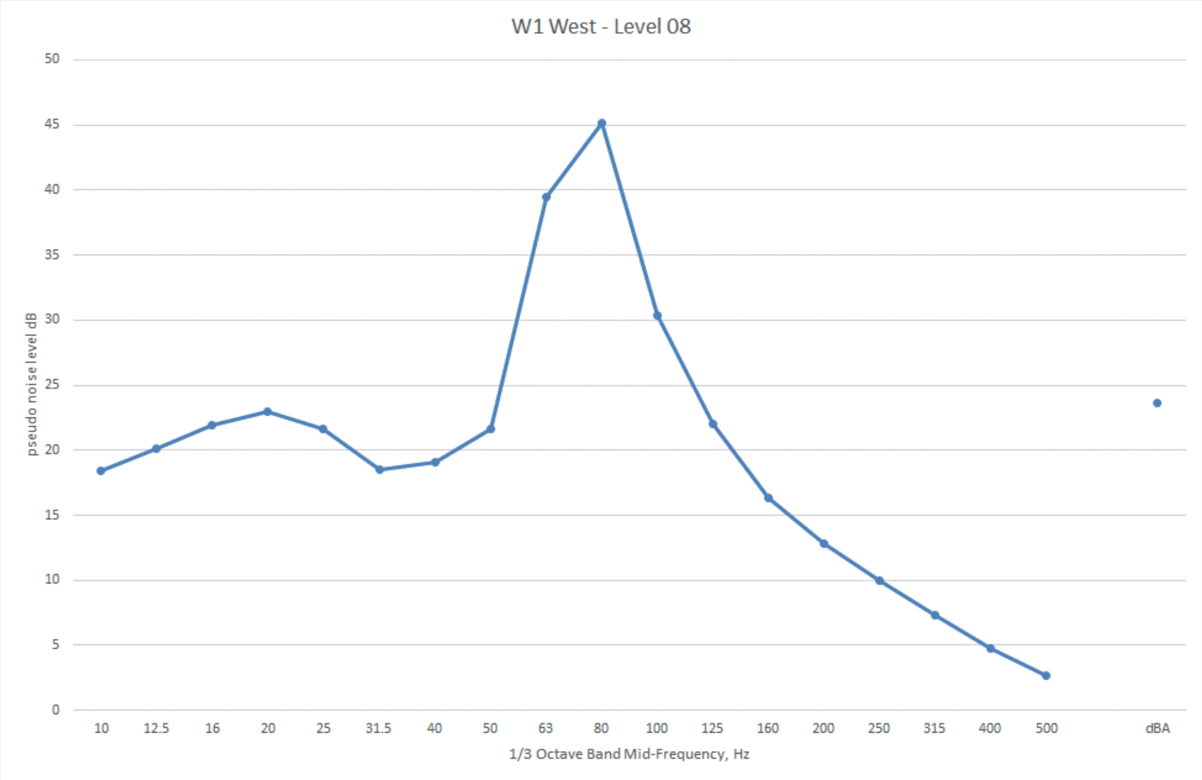


Figure 25 Spectrum for worst case location in Figure 24 – Level 08- West Block

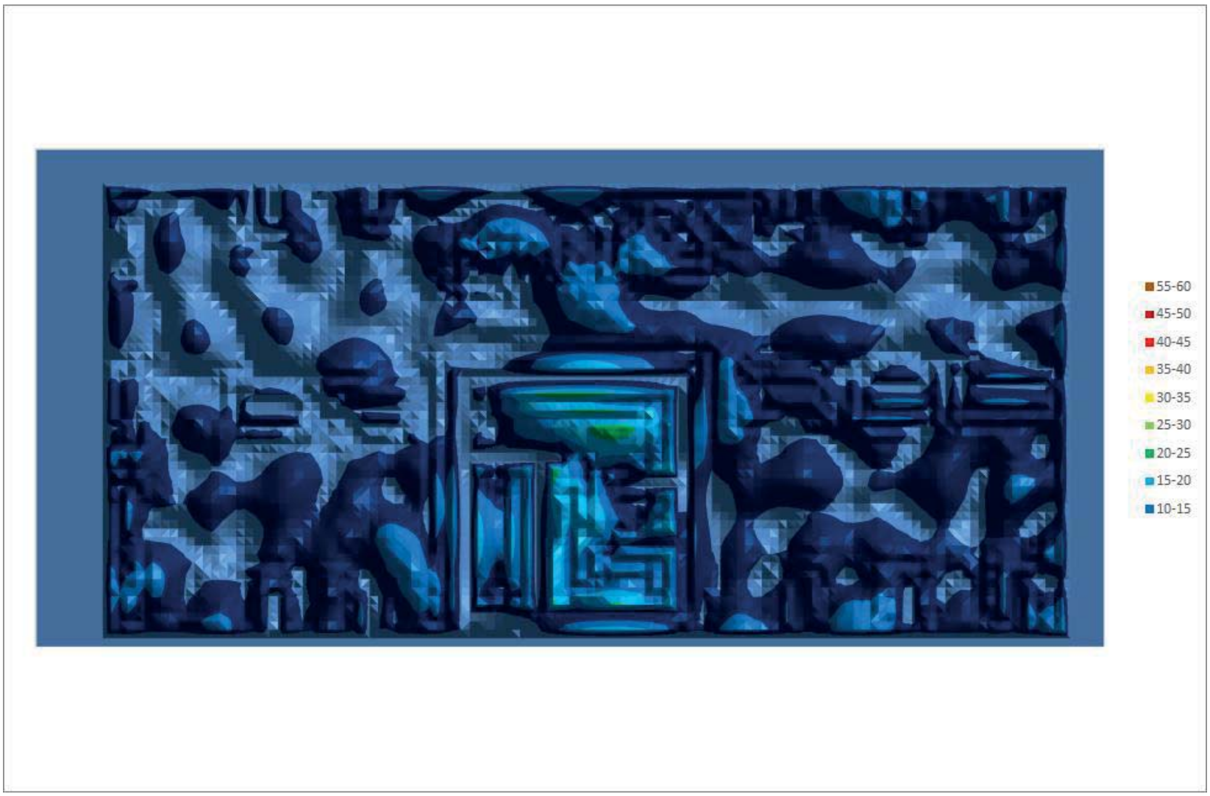


Figure 26 Predicted levels of groundborne noise – Level 09 - West Block

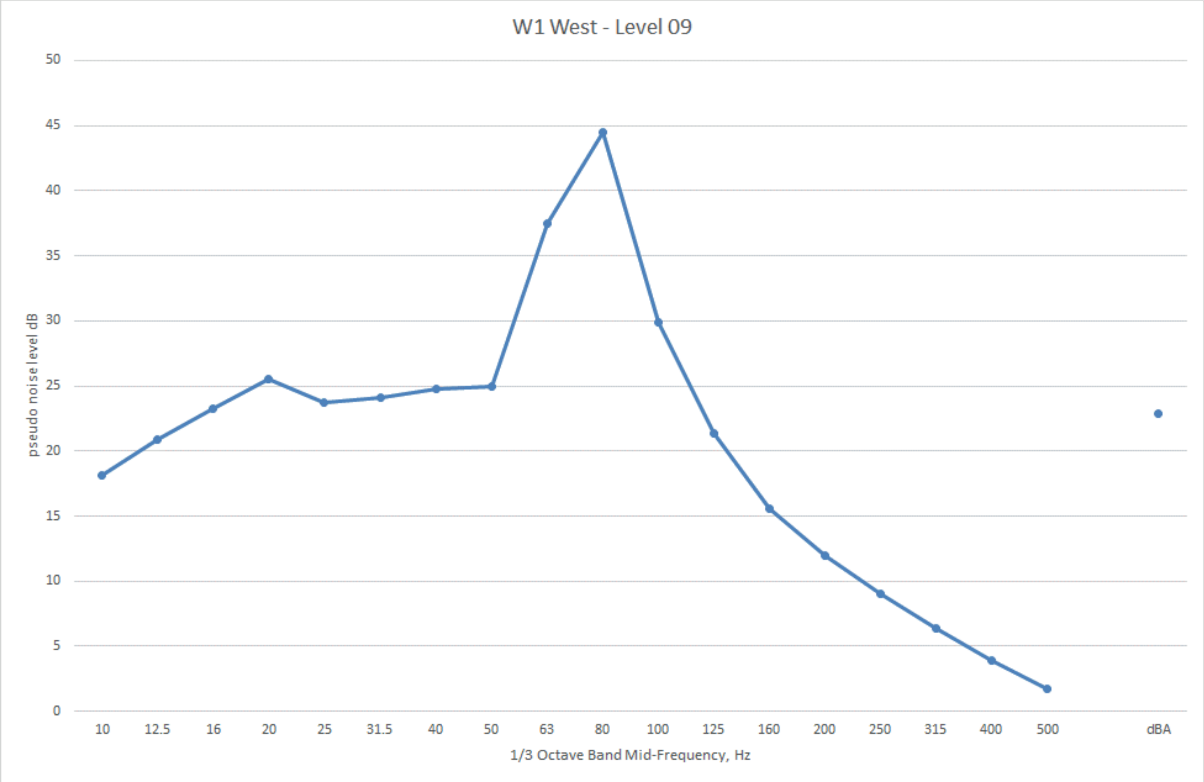


Figure 27 Spectrum for worst case location in Figure 26 – Level 09- West Block

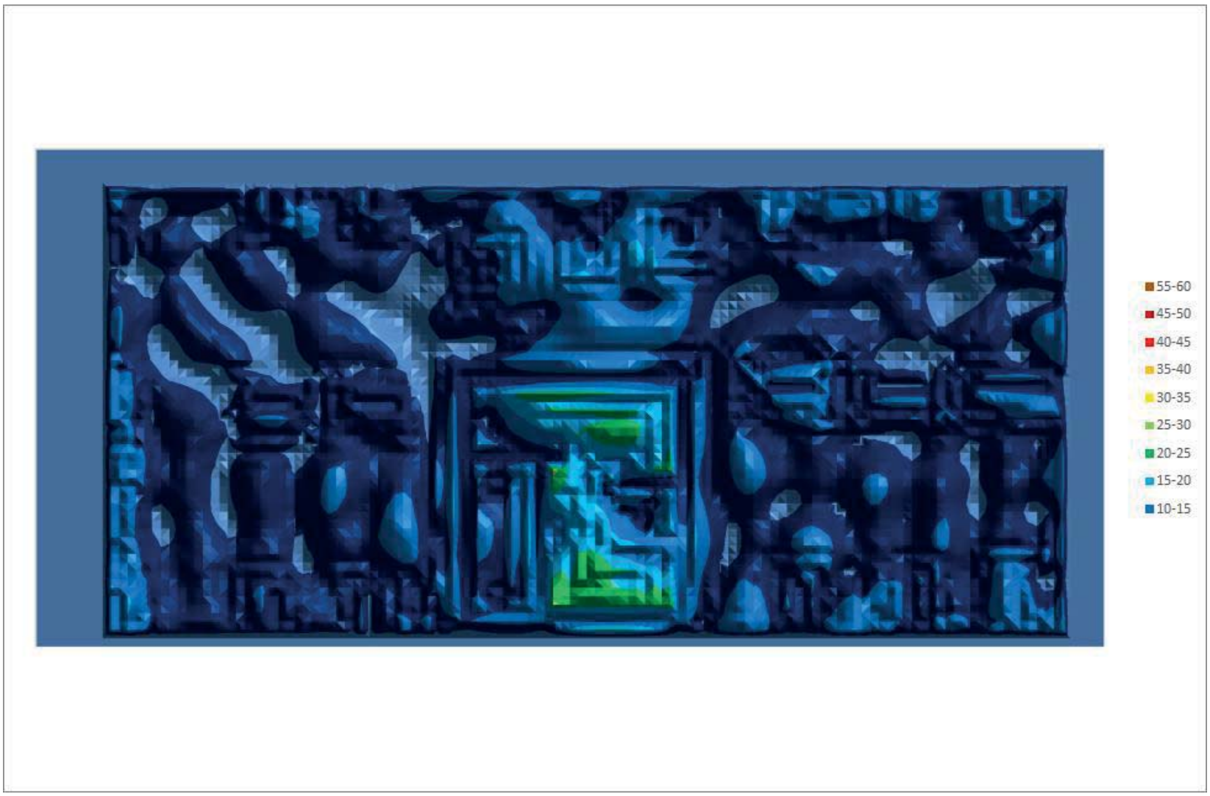


Figure 28 Predicted levels of groundborne noise – Level 10 - West Block

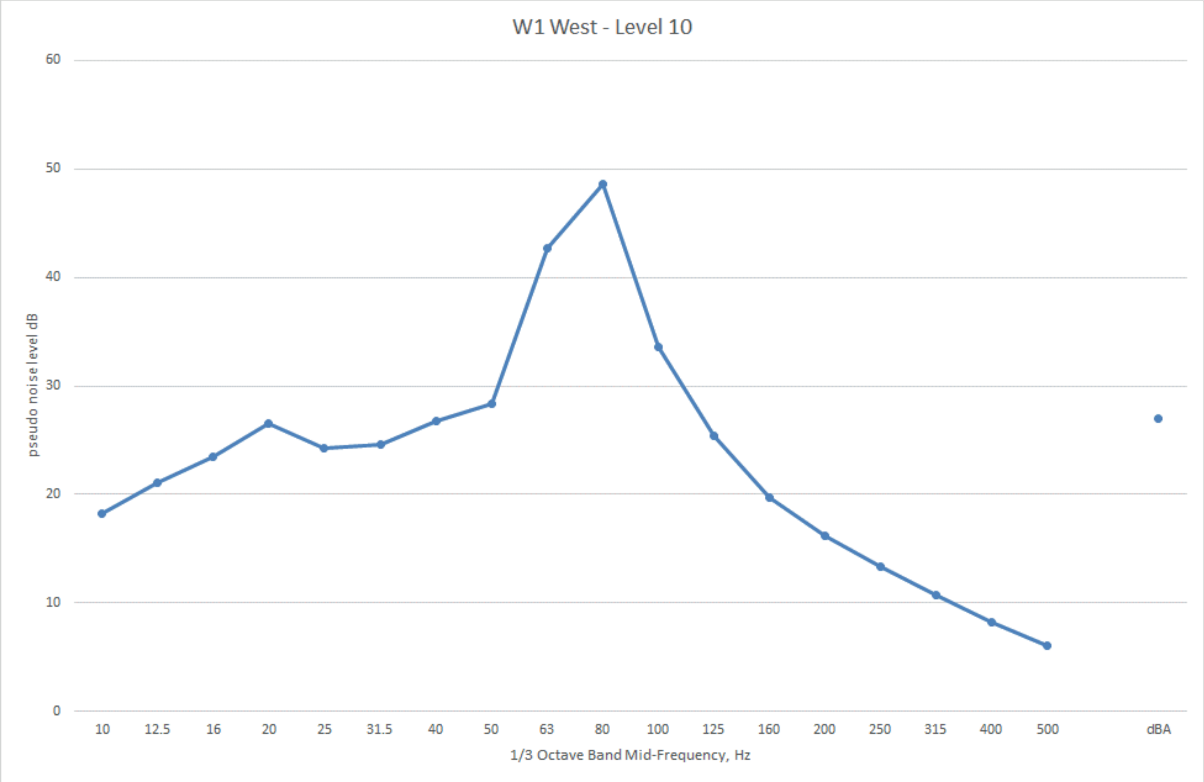


Figure 29 Spectrum for worst case location in Figure 28 – Level 10- West Block

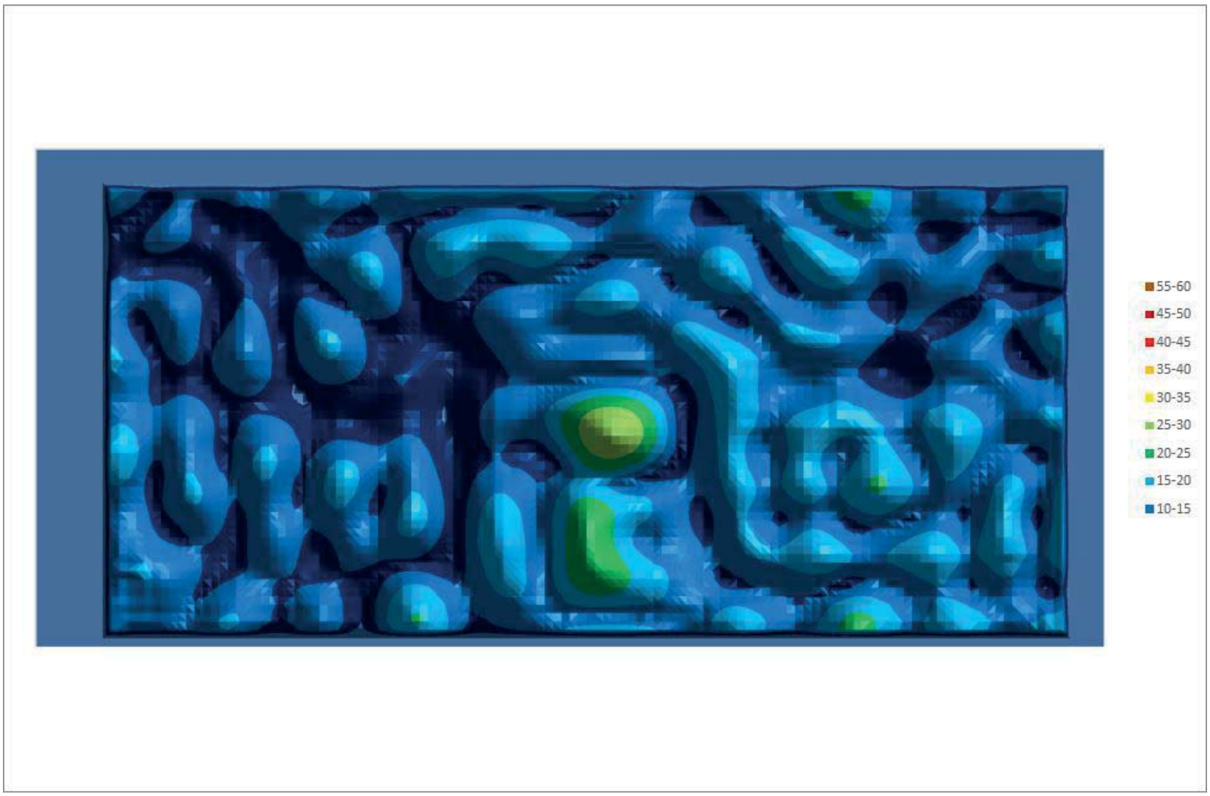


Figure 30 Predicted levels of groundborne noise – Level 11 - West Block

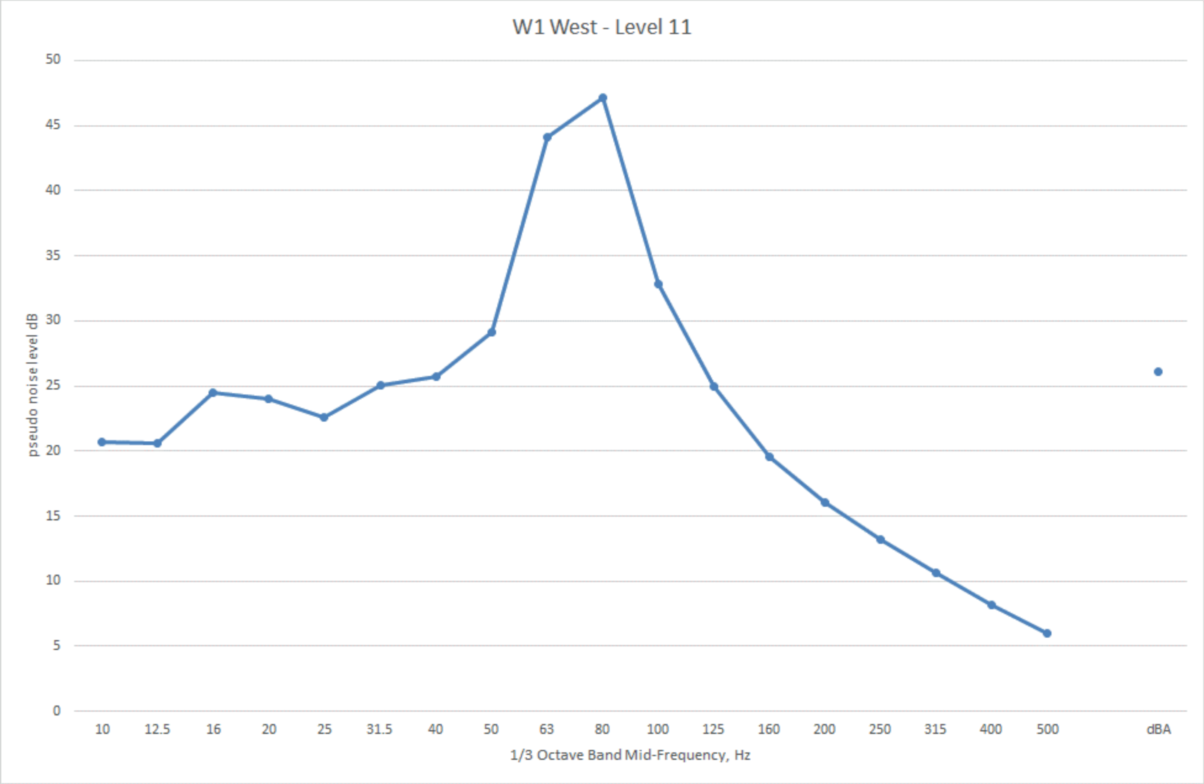


Figure 31 Spectrum for worst case location in Figure 30 – Level 11- West Block

East Block

Podium Level	31 dB L_{ASmax}
Level 01	31 dB L_{ASmax}
Level 02	32 dB L_{ASmax}
Level 03	30 dB L_{ASmax}
Level 04	30 dB L_{ASmax}
Level 05	28 dB L_{ASmax}
Level 06	27 dB L_{ASmax}
Level 07	26 dB L_{ASmax}
Level 08	24 dB L_{ASmax}
Level 09	23 dB L_{ASmax}
Level 10	26 dB L_{ASmax}
Level 11	31 dB L_{ASmax}

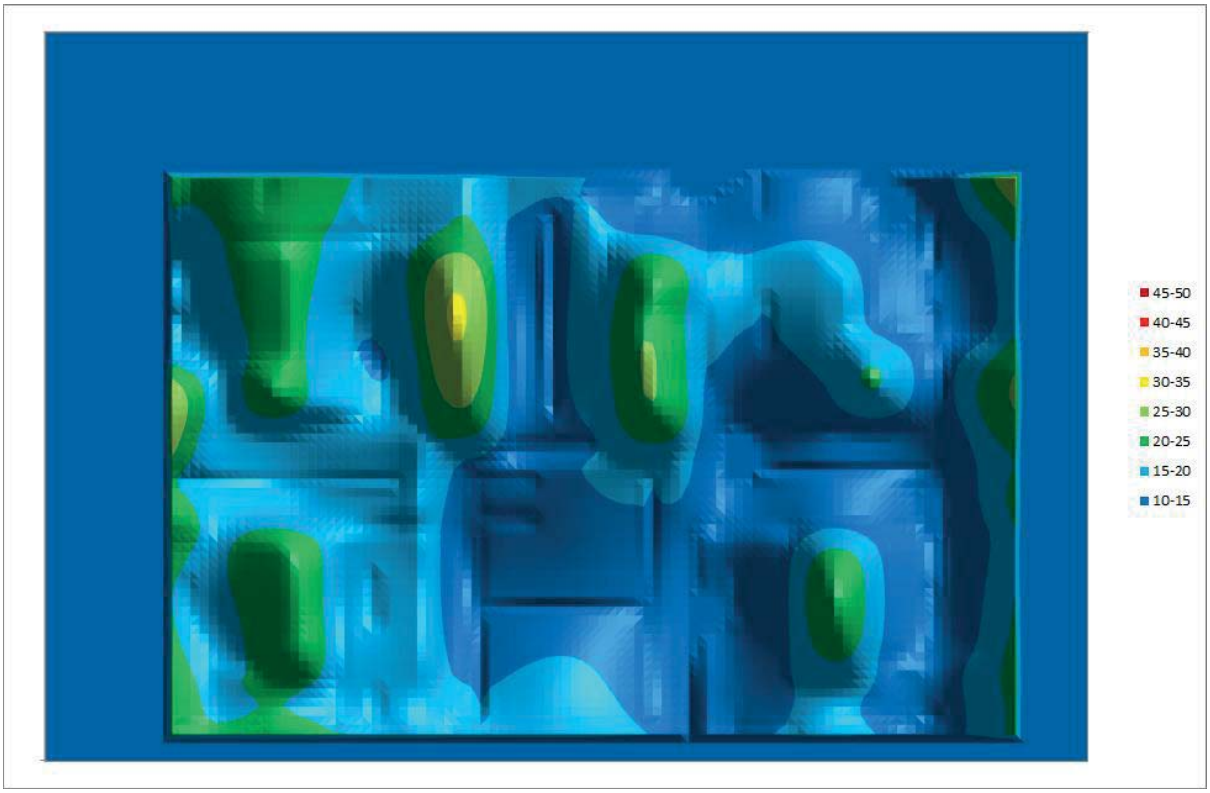


Figure 32 Predicted levels of groundborne noise – Podium Level - East Block

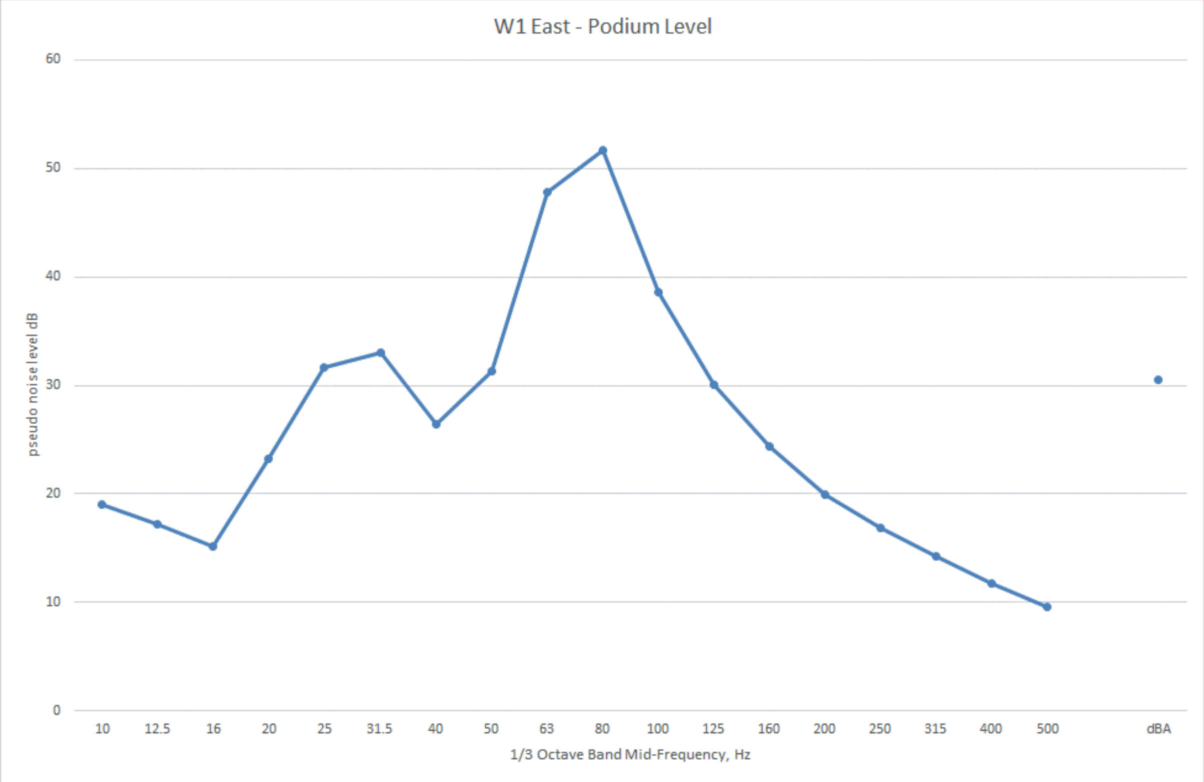


Figure 33 Spectrum for worst case location in Figure 32 – Podium Level- East Block

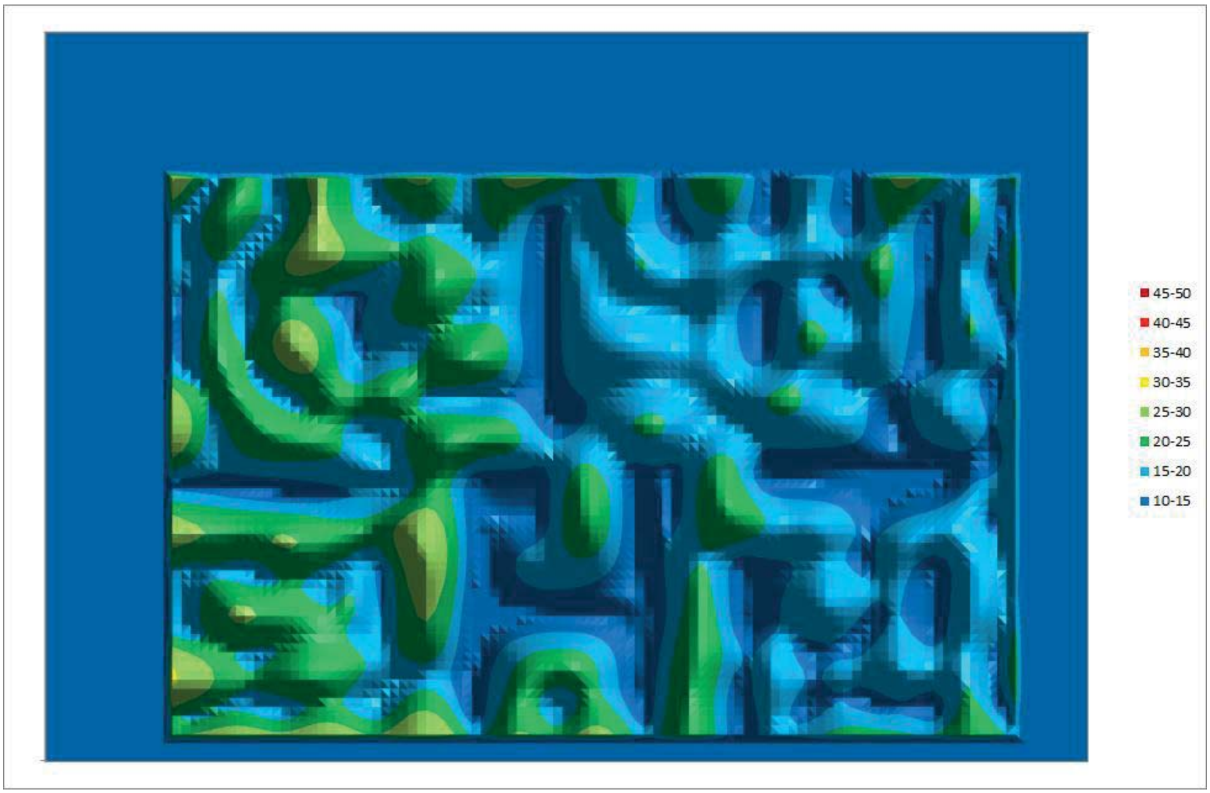


Figure 34 Predicted levels of groundborne noise – Level 01 - East Block

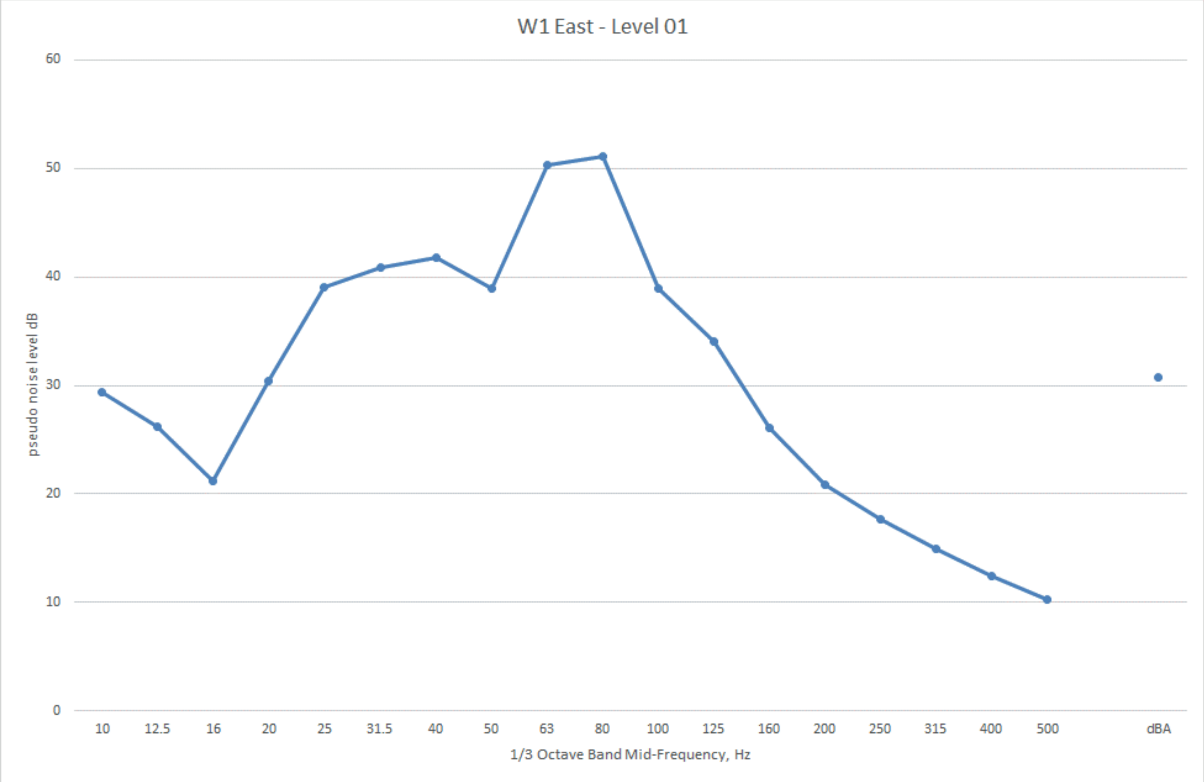


Figure 35 Spectrum for worst case location in Figure 34 – Level 01- East Block

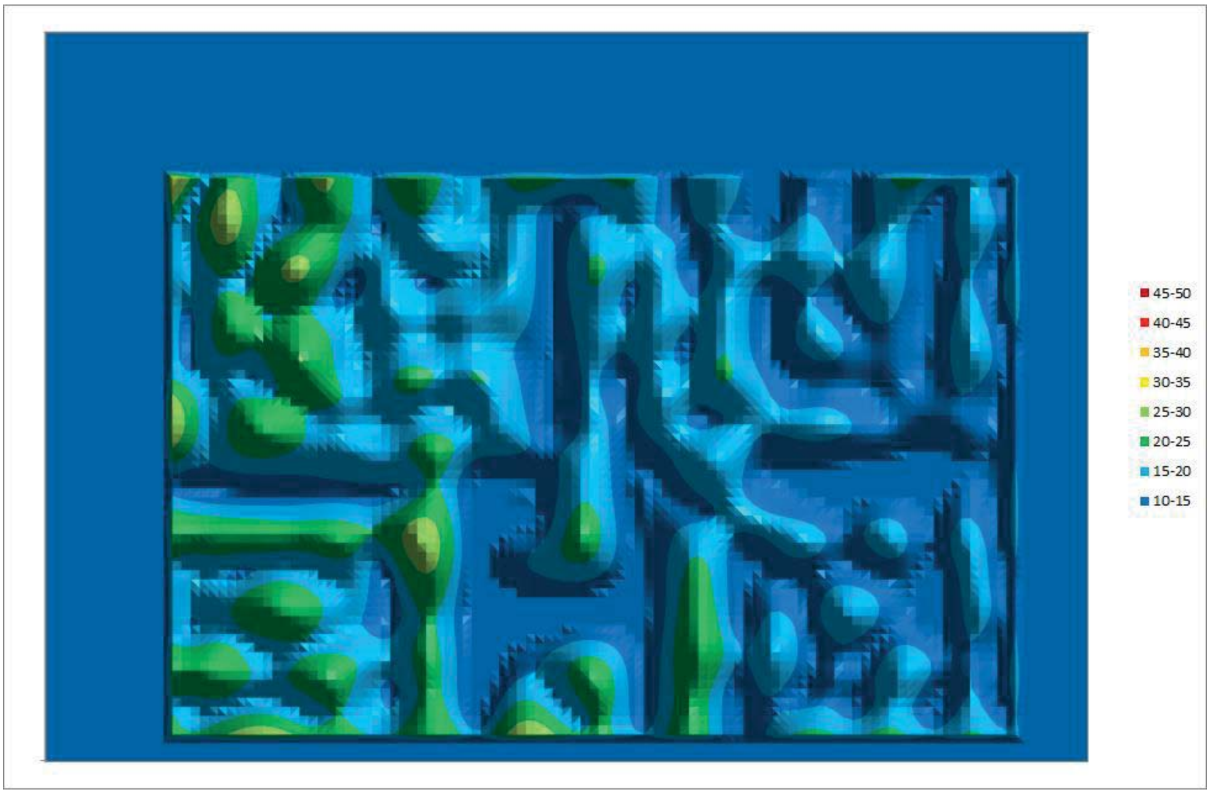


Figure 36 Predicted levels of groundborne noise – Level 02 - East Block

Figure 37 Spectrum for worst case location in Figure 36 – Level 02- East Block

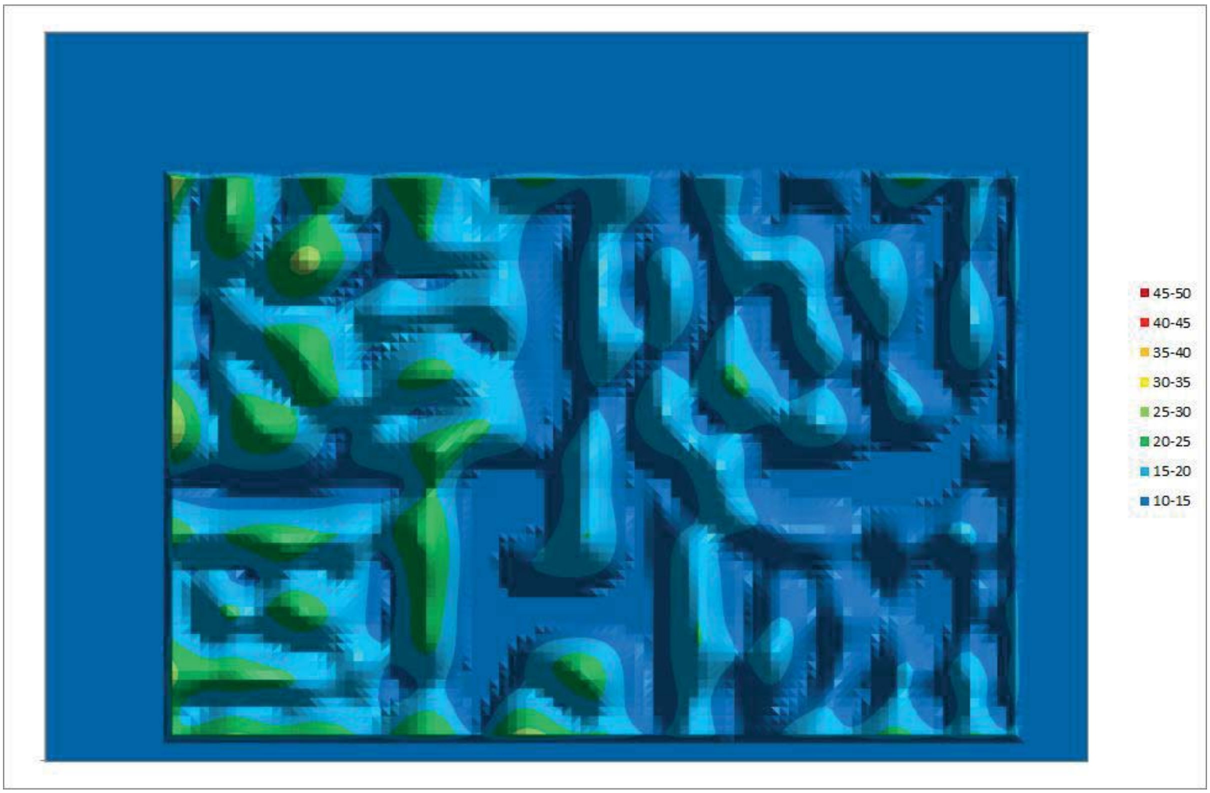


Figure 38 Predicted levels of groundborne noise – Level 03 - East Block

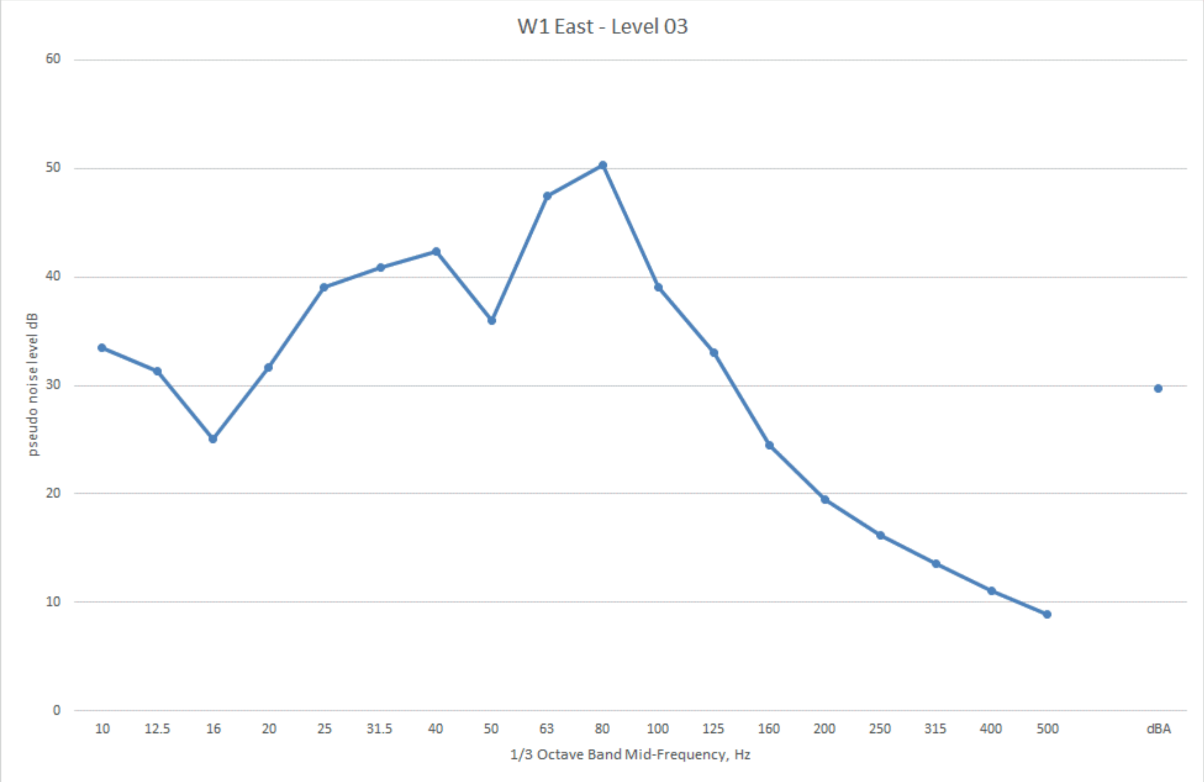


Figure 39 Spectrum for worst case location in Figure 38 – Level 03- East Block

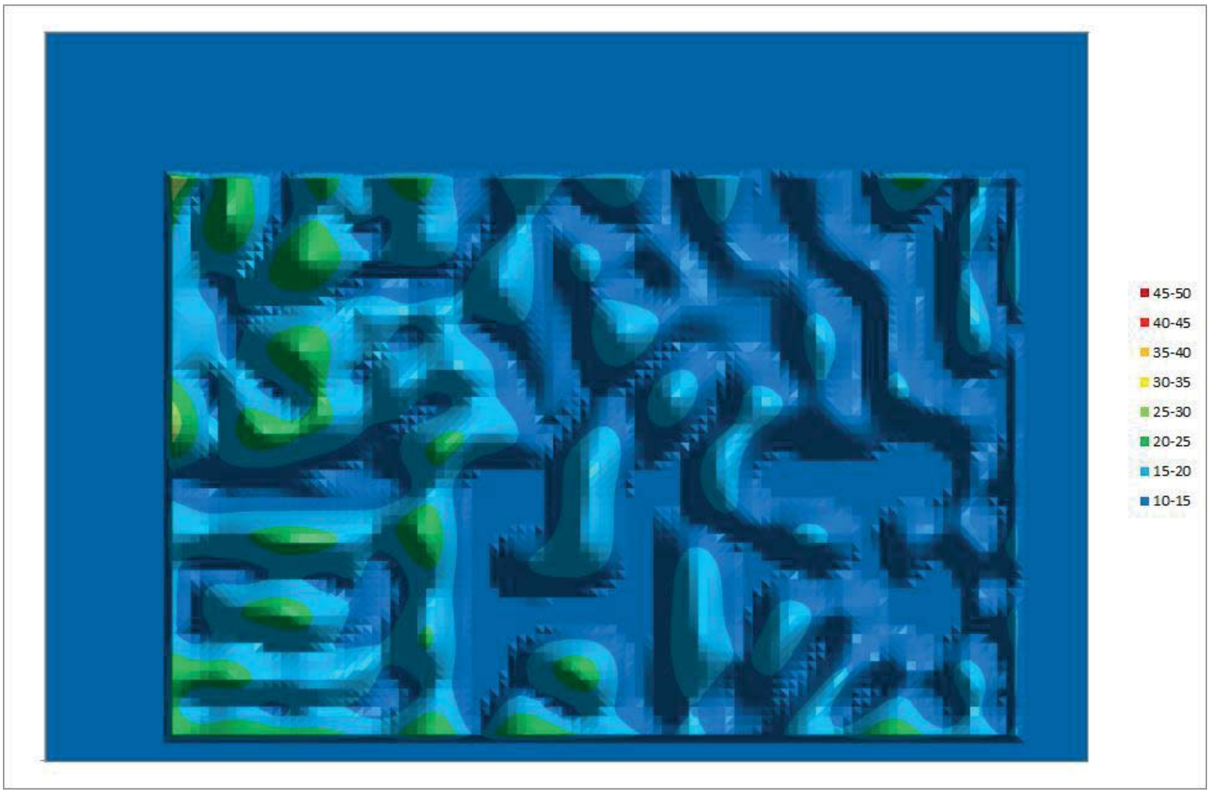


Figure 40 Predicted levels of groundborne noise – Level 04 - East Block

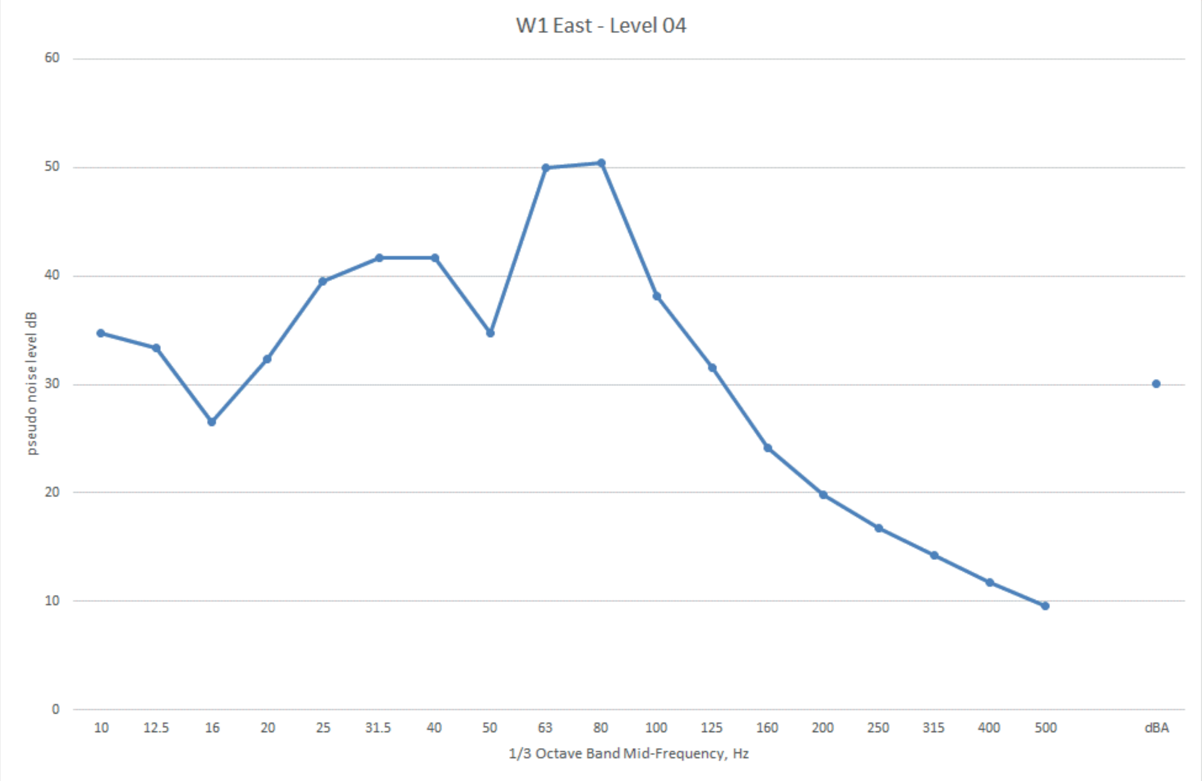


Figure 41 Spectrum for worst case location in Figure 40 – Level 04- East Block

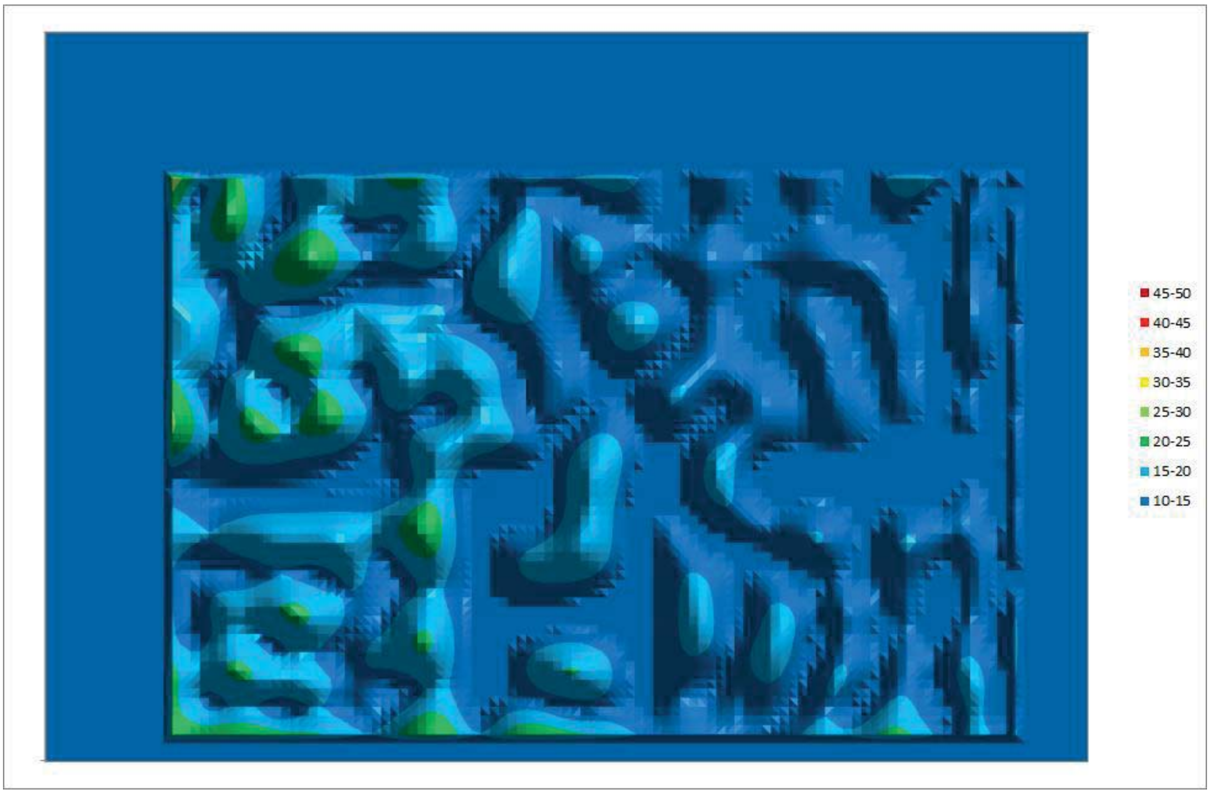


Figure 42 Predicted levels of groundborne noise – Level 05 - East Block

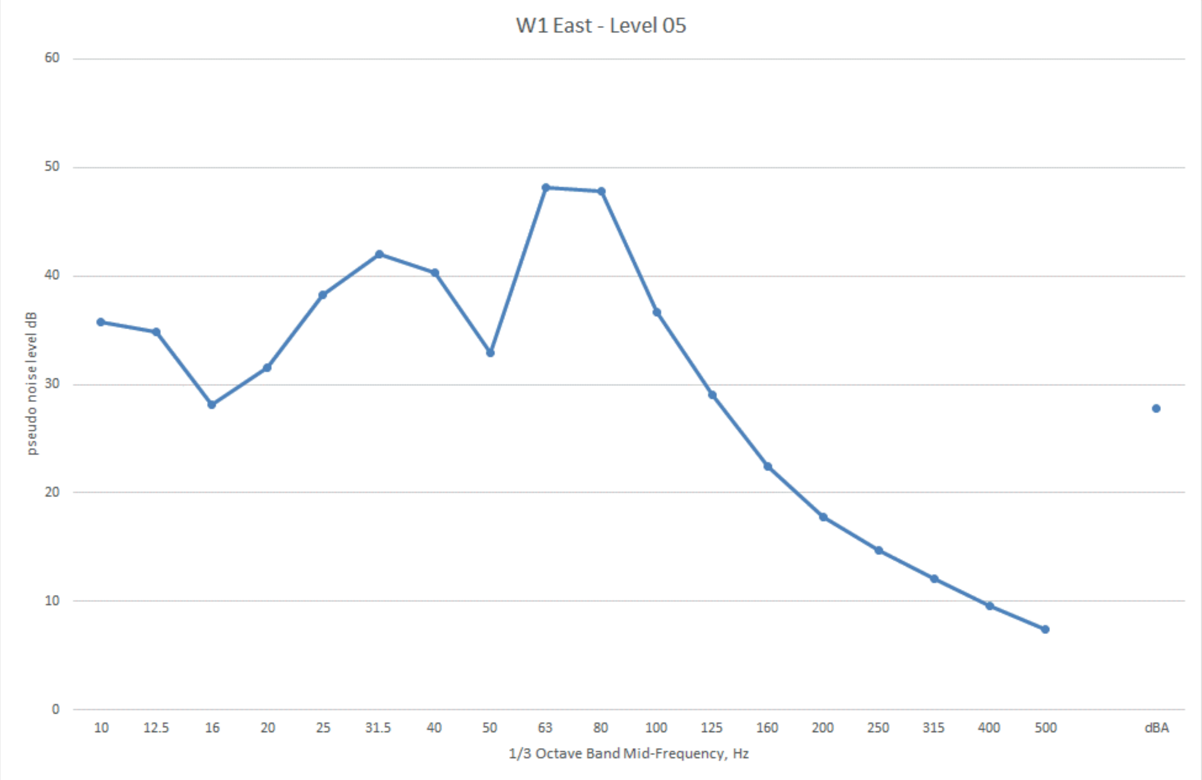


Figure 43 Spectrum for worst case location in Figure 42 – Level 05- East Block

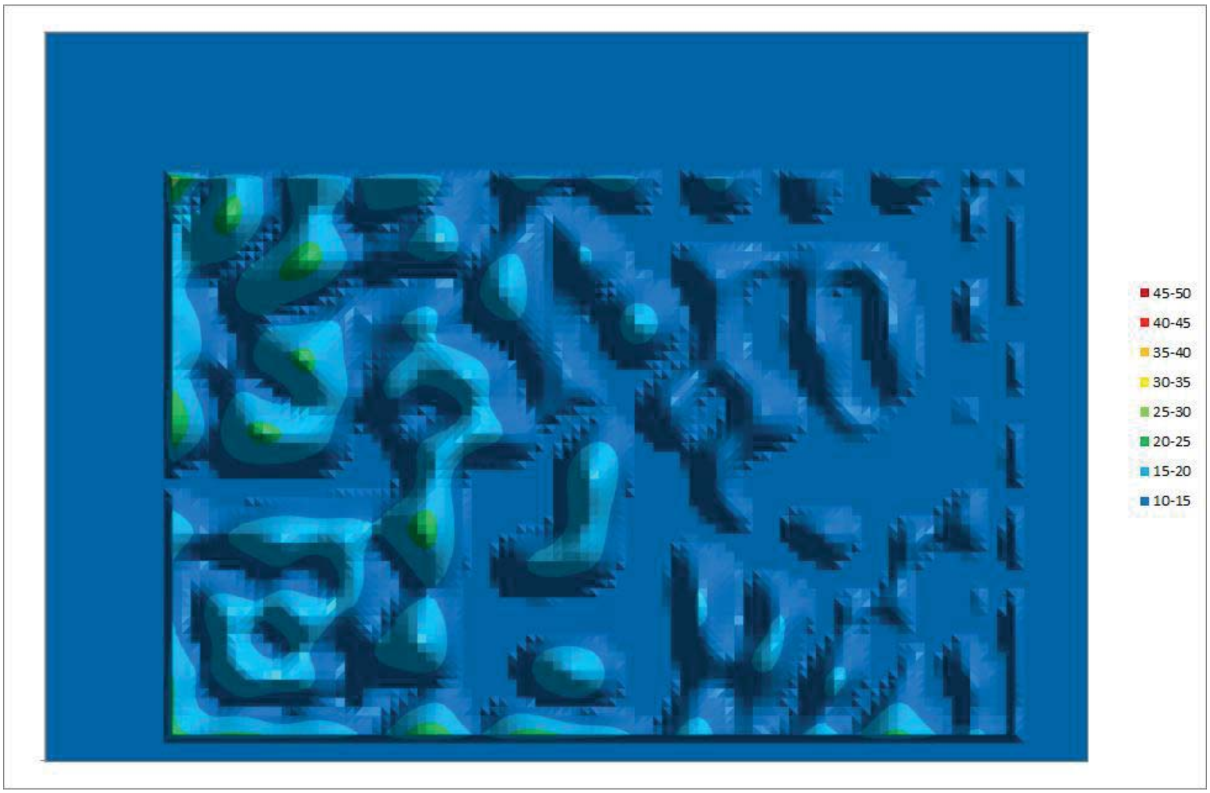


Figure 44 Predicted levels of groundborne noise – Level 06 - East Block

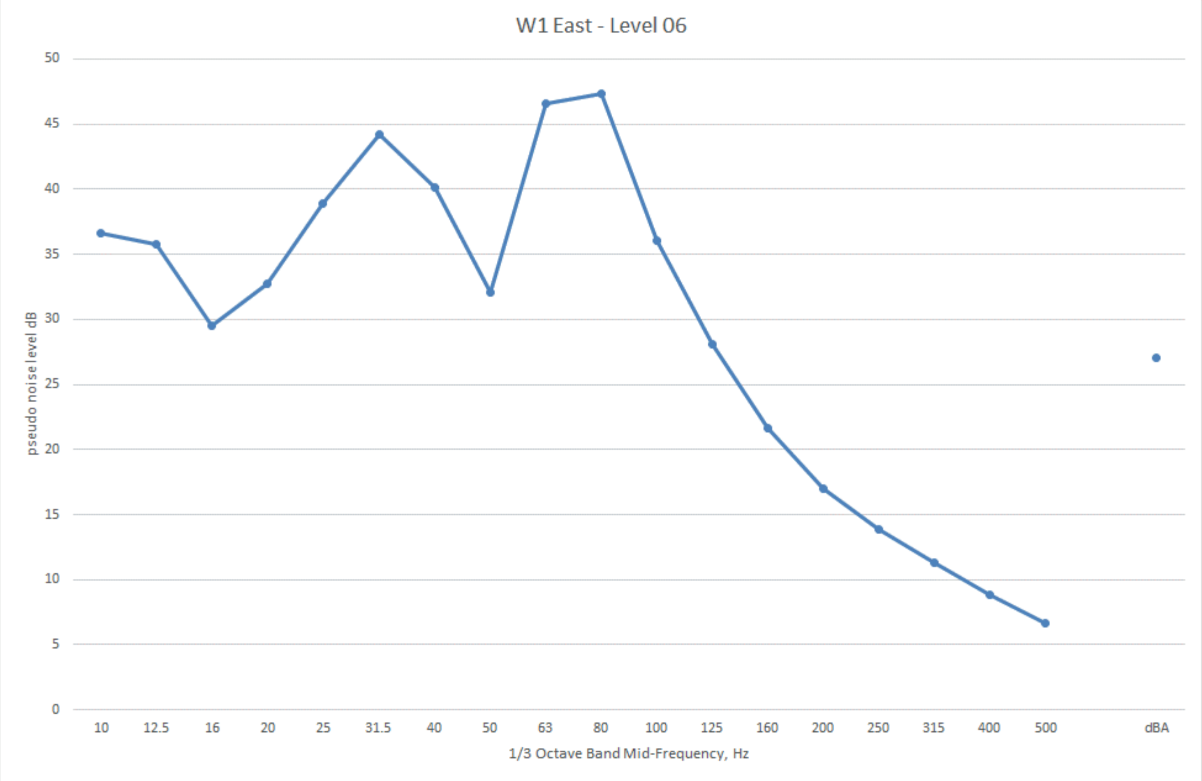


Figure 45 Spectrum for worst case location in Figure 44 – Level 06- East Block

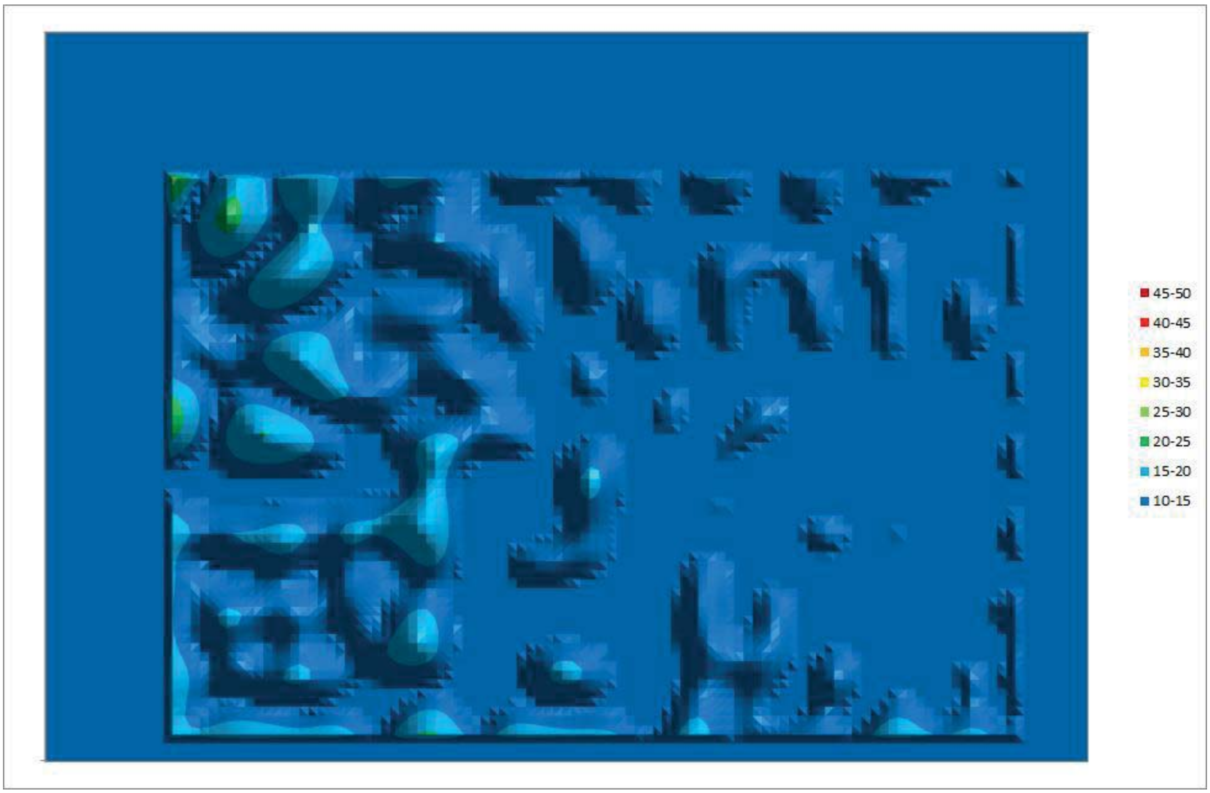


Figure 46 Predicted levels of groundborne noise – Level 07 - East Block

Figure 47 Spectrum for worst case location in Figure 46 – Level 07- East Block

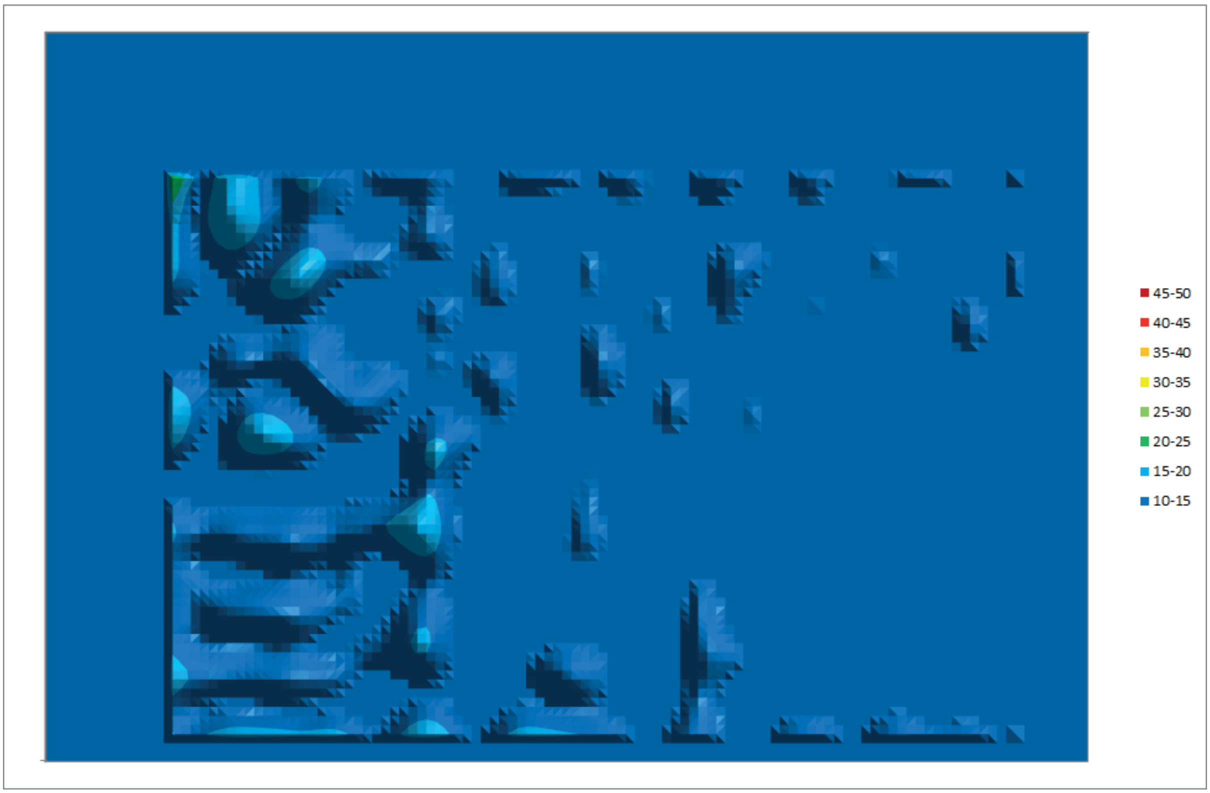


Figure 48 Predicted levels of groundborne noise – Level 08 - East Block

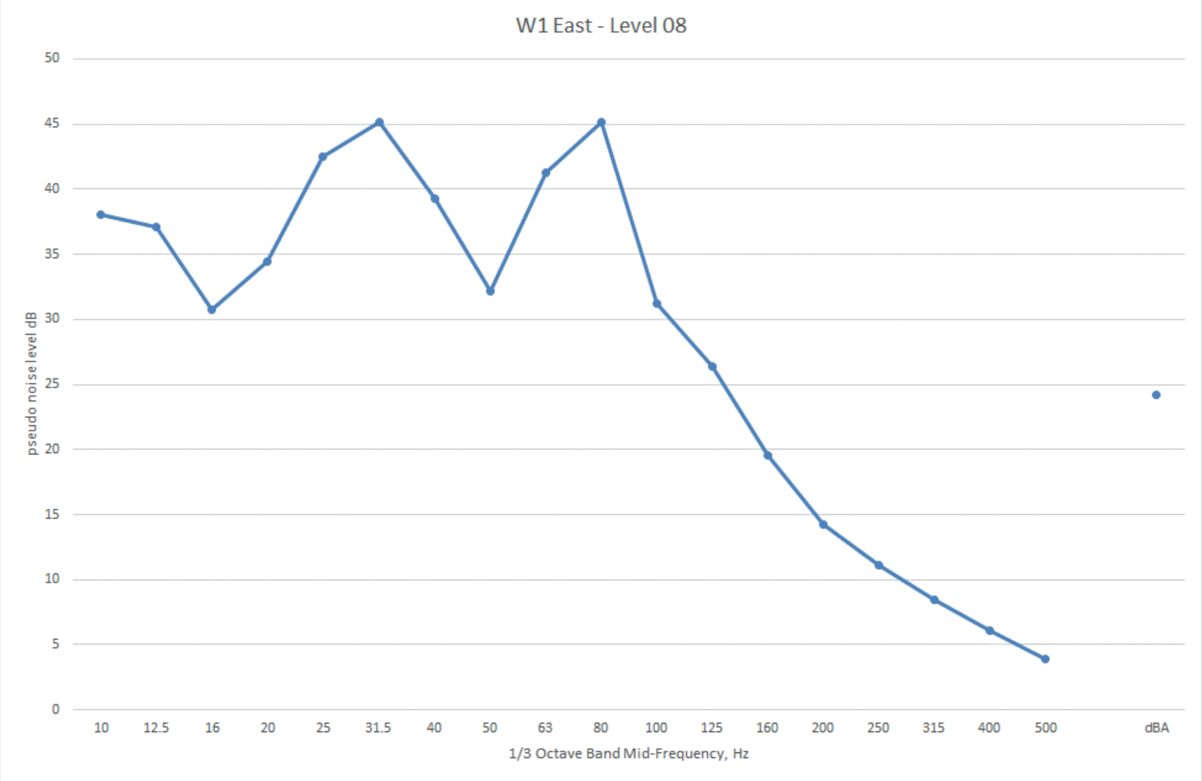


Figure 49 Spectrum for worst case location in Figure 48 – Level 08- East Block

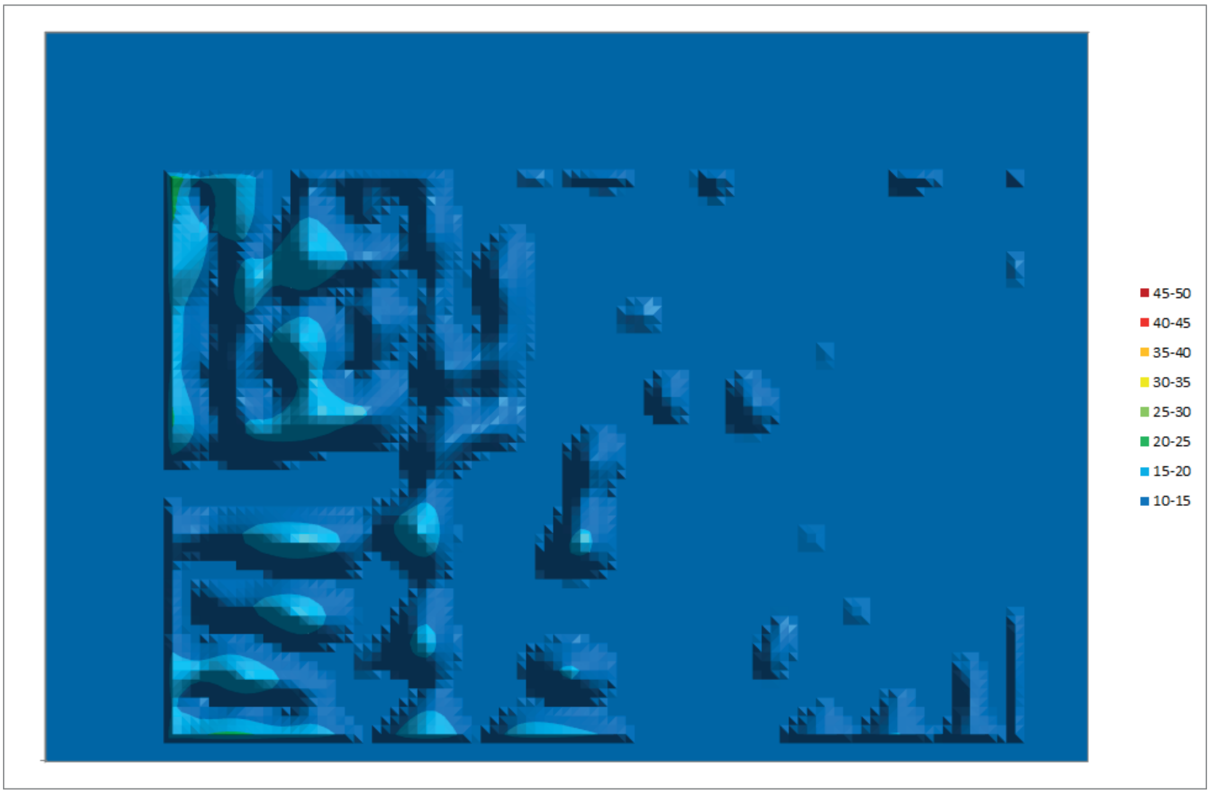


Figure 50 Predicted levels of groundborne noise – Level 09 - East Block

Figure 51 Spectrum for worst case location in Figure 50 – Level 09- East Block

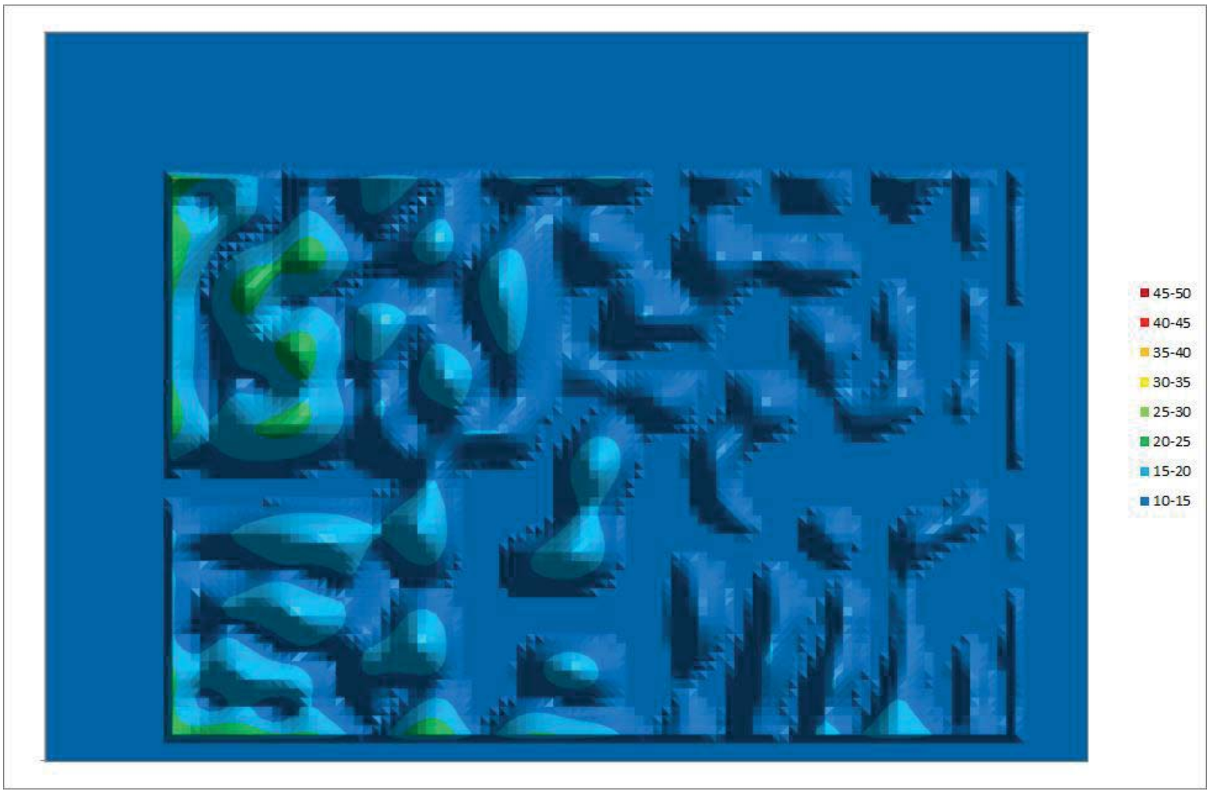


Figure 52 Predicted levels of groundborne noise – Level 10 - East Block

Figure 53 Spectrum for worst case location in Figure 52 – Level 10- East Block

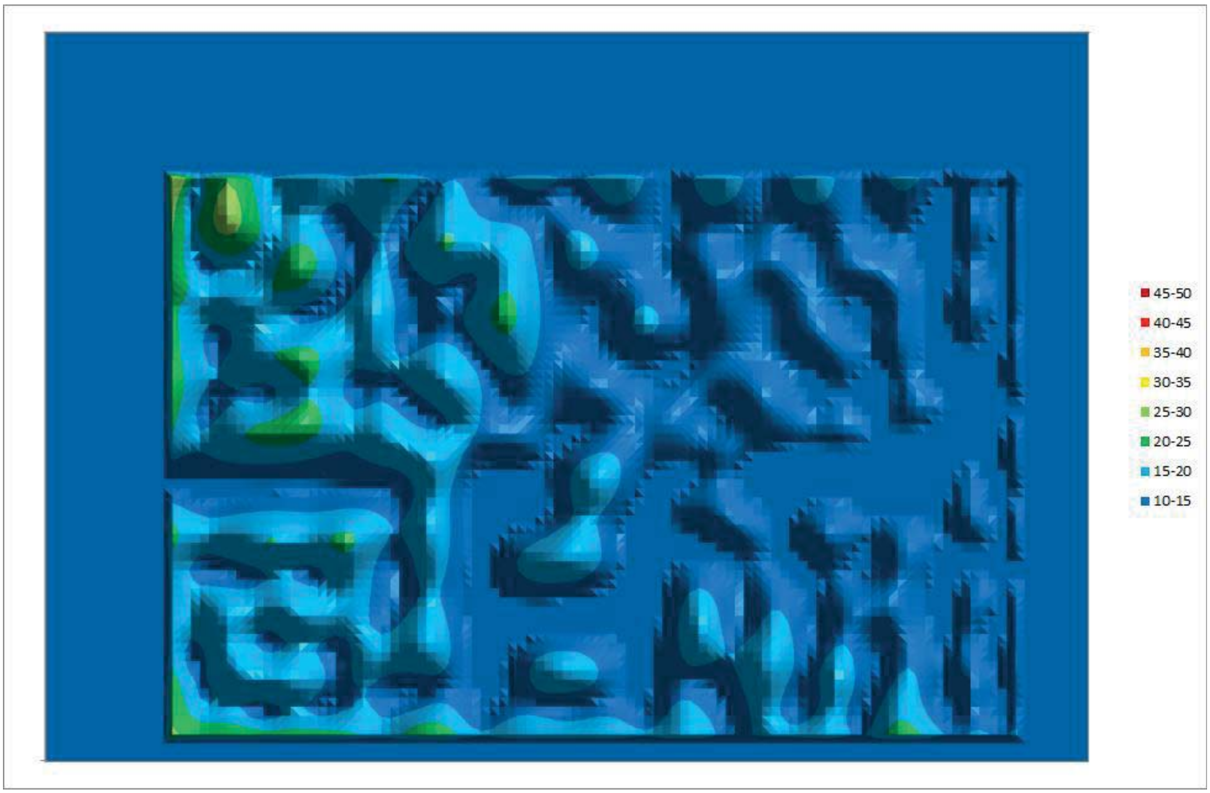


Figure 54 Predicted levels of groundborne noise – Level 11 - East Block

Figure 55 Spectrum for worst case location in Figure 54 – Level 11- East Block

APPENDIX I
List of Drawings

33832 Design Clip 14b.pdf

APPENDIX II

THE *FINDWAVE*® MODEL

A. INTRODUCTION

The model is the finite-difference time-domain (FDTD) model *FINDWAVE*®, proprietary to Rupert Taylor Ltd.

B. OVERVIEW OF *FINDWAVE*

FINDWAVE® is a finite difference time-domain numerical model for computing the propagation of waves in visco-elastic media. While it can be used to solve any acoustical or other 3-dimensional wave propagation problem its principal use is for the modelling of railway noise and vibration.

FINDWAVE® is also capable of modelling the vibration of railways at grade or in underground tunnels, including the transmission of ground-borne noise from the tunnels to the ground surface and into buildings.

The railway implementation of *FINDWAVE*® contains two principal (mutually interacting) modules, the train module, and the track/structure/environment module. The train module represents the train as a stack of damped masses and springs representing the rail vehicle. The excitation is provided from an input file containing either a measured or assumed vertical rail head profile, together with the gravitational effect of the rolling train. The train moves in the model and the location of the contact patch for each wheel is constantly advancing (re-entering the model at the front when it goes beyond the end). The interaction between the contact patch and the rail is transferred to the relevant fixed rail elements using polynomial interpolation as explained in the report.

The track/structure/environment module models the dynamic behaviour of the track and structure supporting the train, and the medium surrounding it, e.g. soil or air, together with structures below or above ground level. The structures concerned are represented as cells in a 3-dimensional orthogonal grid, each cell being assigned density, Lamé constants and loss factor.

Input

For the train module, the input data required are

Train formation
Vehicle length
Bogie pivot spacing
Bogie wheel base
Vehicle body mass
Vehicle secondary suspension stiffness

Secondary suspension damping
Sprung mass of bogie per wheel
Stiffness of primary suspension
Primary suspension damping
Unsprung mass per wheel
Rail mass per metre length
EI of rail
Hertzian contact stiffness
For each layer of rail support:
Stiffness of rail support
Rail support damping
Rail support stiffness
Train speed profile

Rail roughness is read from a file of rail height in millimetres, in steps of not less than 5mm.

For the track/structure/environment module the track, structure and the surrounding space are represented as an array of grid cells, to each of which is assigned a value for density, Lamé constants and loss factor. In the case of air spaces, default values for standard air are provided.

Output

Output data is stored as ASCII data files, suitable for importation into standard spreadsheets such as Lotus 1-2-3 or Excel. The primary output is the velocity or displacement of any software-selectable element in the model for each time step, which may be transformed into the frequency domain and into 1/3 octave or octave spectra. The time domain files may be stored as .WAV files, capable of replay as audible sound through the sound card of a computer.

Selected cross-sections of the model, showing the instantaneous displacement of the elements of the system, can be viewed at any time. For demonstration purposes, a sequence of cross sections can be stored during the running of the program for subsequent replay, after completion of the run, as a sequence showing progress of wave propagation through the cross section.

To perform an acceptably accurate prediction of levels of ground-borne noise in buildings above underground railways it is necessary to take account of

1) The dynamic properties, dimensions, and speed of the rolling stock, and the roughness profile of the wheels.

2) The dynamic properties of the track and its support system, and the roughness profile of the rail running surface.

3) The characteristics of the tunnel

4) The characteristics of the surrounding soil or rock, and of the ground above

5) The characteristics of the building.

All these parameters determine the behaviour of the complete system, which amounts to a complex array of elastic materials, through which wave propagation takes place.

By creating a representation of the system of elastic materials as a three-dimensional array of discrete cells, each possessing the four fundamental properties of an elastic medium[2], namely shear modulus ,compression modulus, density and loss factor, and applying the rules of wave propagation in elastic media, it is possible to represent the real-life behaviour of the system, subject only to the accuracy of the parameters used and the limitations of the size of the cells in the array. For an array with cell sizes tending to zero, and assuming exact knowledge of the dynamic parameters, this approach will precisely represent the real-life behaviour of the system.

Application of the rules of wave propagation in elastic media is done by means of the wave equation. Leaving aside damping temporarily, and assuming initially a homogeneous isotropic medium, the wave equation states that the force acting on a small piece of elastic material will be due to two effects. Firstly, change of volume with distance will produce a force in that direction proportional to the compressive modulus of the material and the rate of change of volume with distance (i.e. the force is proportional to the pressure gradient). Secondly, change of shear angle with distance will produce a force in the direction of the shear (at right angle to the distance direction) proportional to the shear modulus of the material and the rate of change with distance.

C. THE ALGORITHMS

The wave equation in differential form is as follows

$$\mu\left(\frac{\partial^2\xi}{\partial x^2}+\frac{\partial^2\xi}{\partial y^2}+\frac{\partial^2\xi}{\partial z^2}\right)+(\lambda+\mu)\left(\frac{\partial^2\xi}{\partial x^2}+\frac{\partial^2\eta}{\partial x\partial y}+\frac{\partial^2\zeta}{\partial x\partial z}\right)=\rho\frac{\partial^2\xi}{\partial t^2} \tag{1}$$

---

[2] these can be different for each direction

for the *x* axis, with corresponding equations for the *y* and z axes, where *x, y, z* and ξ, η, ζ are displacements in three orthogonal axes; λ and μ are Lamé constants and ρ is the density. The Lamé constant μ is also known as the shear modulus, *G*. The Lamé constant λ is also known as the coefficient of dilatation and is given by

$$\lambda = \frac{2\sigma G}{(1-2\sigma)}$$

where σ is Poisson's ratio.

Equation (1) can be stated in finite difference form by replacing the differential operator with the approximation

$$\frac{\partial \xi}{\partial x} \approx (x[i][j][k] - x[i-1]\ [j][k]) / \Delta x \qquad (2)$$

For $\Delta x \rightarrow 0$ these two forms are identical.

For a homogeneous, isotropic medium with a finite value for Δx, Δy and Δz, elastic wave propagation can be computed using the finite difference substitution of equation (2)

Effectively, the process is as follows, for each axis, i, j and k. The example given is for axis i. Each point p(i,j,k) lies at the corner of a rectangular cell and is assigned a mass equal to one eighth of the sum of the eight contiguous cells as well as a displacement and velocity. The displacement and velocity is interpolated for each intermediate "virtual" point p(i+d,i+d,k+d) where d=0 or 0.5.

1) Compute pressure gradient
2) Compute shear force gradient
3) Accelerate p(i,j,k) by $\Delta v = F/\rho\ \Delta t$ where *F* is the sum of the force 1 & 2 and ρ is the density assigned to the point and *v* is the point velocity.
4) Displace p(i,j,k) by $\Delta x = \Delta v * \Delta t$ where *x* is the point displacement and *t* is one time step.
5) repeat from step 1

The geometric part of wave propagation is completely represented by this process. Further terms are required to represent damping. Of several possible terms, the inclusion of a coefficient by which the velocity is multiplied produces a loss factor which decreases within increasing frequency (and gives rise to an excess attenuation per unit distance which is independent of frequency). A viscous damping term can be used, by including a force proportional to acceleration multiplied by a coefficient. However, many materials exhibit hysteretic damping, or damping with other types of frequency dependence. To model these effects it is necessary to include an algorithm which implements Boltzmann's strain history method where

$$s(t) = D_1\varepsilon(t) - \int_0^\infty \varepsilon(t-\Delta t)\varphi(\Delta t)d(\Delta t)$$

where $\varphi(\Delta t) = \frac{D_2}{\tau}e^{-\Delta t/\tau}$ is an after-effect function, D_2 is a constant and τ is a relaxation time. D_1 is a modulus, $s(t)$ is stress and $\varepsilon(t)$ is strain. By combining several after-effect functions with different values of D_2 and τ any relationship between loss factor and frequency may be represented. Note that in the frequency domain the integral has a real and imaginary part, with the result that the value of the modulus is reduced by the inclusion of the relaxation terms. Depending on the choice of the constants and relaxation times, the stiffness of a resilient element will be frequency-dependent, and the value of D_1 must be adjusted at the same time that D_2 and τ are selected to give the required dynamic stiffness. This method has been implemented in the version of *FINDWAVE®* used for this study.

In principle the entire system can be represented by appropriate coding of cells to represent the vehicle body, suspension, bogies, wheels etc. In the present implementation, however, the train is represented as a set of stacks of lumped masses and springs, since the unsprung mass of wheels is by far the most influential parameter of the vehicle, and coupling between wheels, between axles and between bogies is normally insignificant.

For each wheel, the stack is as follows:

1) Mass, ρ_3, equal to one-eighth of the vehicle body mass for a four-axle vehicle.

2) Spring of stiffness K_2 and damping rate (Ns/m) C_2 one quarter of the secondary suspension.

3) Mass, ρ_2, equal to one quarter of the sprung bogie mass

4) Spring of K_1 and damping rate (Ns/m) C_1 equal to that of the primary suspension per wheel.

5) Mass, ρ_1, equal to the half the unsprung mass per axle.

6) Spring, K_h, with stiffness equal to the Hertzian contact spring stiffness (assumed to be 1.2 GN/m)

The finite difference algorithm applied to the stack of masses and springs is as follows:

1) Compute compression Δz_h on Hertzian contact spring from difference between the displacement of the wheel mass and the displacement of the rail, minus the displacement of the roughness profile.

2) Accelerate unsprung mass by $\Delta v_l = -K_h \Delta z_h / \rho_l \ \Delta t$ where K_h is the stiffness of the Hertzian contact spring and ρ_l is the unsprung mass.

3) Accelerate the unsprung mass by $\Delta v_g = -g \Delta t$ where g is gravitational acceleration.

4) Accelerate rail cell by $\Delta v_r = K_h \Delta z_h / \rho_r \ \Delta t$ where K_h is the stiffness of the Hertzian contact spring and ρ_r is the mass of the rail cell

5) Compute the compression of the primary suspension as the difference between the displacement of the sprung mass and the unsprung mass.

6) Accelerate sprung mass by $\Delta v_2 = -\{K_1 \Delta x_1 + C_1(v_2 - v_1)\}/\rho_2 \Delta t$ where K_1 is the stiffness of the primary suspension spring.

7) Accelerate the sprung mass by $\Delta v_g = -g \Delta t$ where g is gravitational acceleration.

8) Accelerate unsprung mass by $\Delta v_l = \{K_1 \Delta x_1 + C_1(v_2 - v_1)\}/\rho_1 \Delta t$.

9) Compute the compression Δz_2 of the primary suspension as the difference between the displacement of the vehicle body mass and the sprung mass.

10) Accelerate vehicle body mass by $\Delta v_2 = -\{K_2 \Delta x_2 + C_2(v_3 - v_2)\}/\rho_3 \Delta t$ where K_2 is the stiffness and C_2 the damping rate of the secondary suspension spring and ρ_3 is the vehicle body mass.

11) Accelerate the vehicle body mass by Δv_g=-gΔt where g is gravitational acceleration.

12) Accelerate sprung mass by $\Delta v_2=\{K_2\Delta x_2 + C_2(v_3-v_2)\}/\rho_2\Delta t$.

13) Displace the rail cell by $\Delta z_r=v_r\Delta t$

14) Displace the unsprung mass by $\Delta z_1=v_1\Delta t$

15) Displace the sprung mass by $\Delta z_2=v_2\Delta t$

16) Displace the vehicle body mass by $\Delta z_3=v_3\Delta t$

17) Compute new velocities and displacements for all cells in the structure/environment module

18) Repeat from (1)

The rail is represented as a line of cells with properties which give it the mass per unit length and bending stiffness appropriate to the rail section concerned.

The location of the contact patch between wheel and rail moves at the speed of the train. The displacement of the rail, which is computed at steps equal to the longitudinal cell size, is determined for the precise position of the contact patch by polynomial interpolation. This interpolated displacement is used to compute the compression of the contact spring. The force produced by the contact spring is applied not only to the wheel, but also to the two ends of the rail cell in proportion to the distance of the contact patch from the opposite end of the cell.

For cases where the dynamic properties vary significantly, for example a solid component surrounded by air, manipulation is necessary to achieve correct results at the boundary of the solid and the air. The *FINDWAVE*® implementation achieves this by staggering the grid so that cell masses, elastic and damping constants are defined for points p(i+½,j+½,k+½) while displacements and velocities are computed for points p(i,j,k) and interpolated for points p(i+½,j+½,k+½). Volumes and shear angles are computed for eight sub-sections of each cell.

D. BOUNDARIES

For modelling finite objects fully surrounded by space, the boundaries can be represented by assigning zero-valued elastic moduli to the space provided that the acoustic load of the air in an airspace can be neglected. If radiation into air is to be modelled, or if an infinite or semi-infinite medium such as the ground is required, it is necessary to minimise the effect of reflections from the boundaries. For a train tunnel, where distances to be modelled are small compared with the length of the train, the z-axis boundaries are dealt with by creating a model exactly one rail vehicle (or unit of several coupled rail vehicles) in length, and then connecting the ends of the model together to create an infinitely long train. This is done by copying the cell displacements and velocities from one end of the model to the other end at the end of each time-step.

For the other boundaries in the x- and y-axes, the potential problem of spurious reflections from model boundaries is overcome by the use of an impedance matching technique. This effectively assigns to the cells which are required to be non-reflective on the boundaries of the model the properties of a massless viscous damper such that

$$\frac{\eta K''}{\omega} = -\left(\rho c + \frac{D(\xi_o - \xi_{-1})}{\rho \Delta x v_0} \Delta t \right)$$

where η is the loss factor (dimensionless), *K”* is the imaginary part of a complex spring stiffness in which the real part is zero, ω the angular frequency, ρc the characteristic impedance of the medium, ξ_0 and ξ_{-1} are the displacements of cell points 0 and –1 where the boundary is at cell 0, ρ is the density of the cell contents and v_0 is the velocity of cell 0. Over 95% absorption is achieved across the spectrum.

E. INPUT DATA

The only input data required for the model are the masses of each cell, plus the shear modulus and the compression modulus, and the loss factor. A rail/wheel roughness profile is also required. Otherwise, all secondary parameters such as wave speeds, impedances etc. are automatically generated by the finite difference algorithm. The only other input relates to methods of approximating actual structure shapes using the orthogonal grid.

The output of the model consists of a file containing the displacement and/or velocity of one or more selected cells.

The time steps used are of the order of 30 to 60 microseconds, and the model is run for either 16384 or 32768 steps to give a signal length of just under 1 second.

The resulting discrete time series can then be subjected to discrete fourier transformation to yield frequency spectra.

Note that, whereas in the acoustical analogy, the impedance of air varies little (except close to sources such as points), so that in most cases power is proportional to velocity squared, in elastic media, velocity transfer functions do not directly convey information about power transmission, and velocity at the receiver, in a low impedance medium, can be higher than velocity near the source, in a high impedance medium, even when there are power losses between the source and the receiver.

F. VALIDATION

The finite difference algorithm is validated by creating models of structures for which algebraic solutions are available and comparing the eigenfrequencies and decay rates. For Timoshenko beams, plates, thin and thick cylinders the eigenfrequencies are correctly predicted.

APPENDIX B – TRACKFORM USED BY NETWORK RAIL

Table 4: Summary of requirements and preliminary track specification

Detail/Requirement		Sonneville LVT Booted Single Block
Supplier	Slab track supports	Vigier (CH, system supplier); Getzner (AT, pad supplier)
	S&C	Any
Installed	UK/Europe	UK (East London Line), Switzerland, Spain, Sweden, Denmark
	Rest of World	Hong Kong, S. Korea, USA, S. Africa
	Similar Operating conditions	Yes
NR60 RE/PW compatibility		Yes
Points Operating Equipment – Mk2 Clamplock with 4’ conventional backdrive.		Selected in joint meeting with suppliers, Thameslink N306 project and Network Rail HQ 25/05/11). New boot system required for Schwihag Clamp lock hollow bearer (IBCL) (supply and testing requirements to be developed for Canal Tunnels Junction in 2011).
Stiffness of layout		Achieved through mostly point supports as plain line (some block support 2 rails/crossing in S&C)
Transition to soft adjacent trackform		Only applied in Canal Tunnels Junction section of the project.
Vibration mitigation in Plain Line		HA-LVT version
Vibration mitigation in S&C		Block pads in S&C to be supplied to match
Sleeper spacing		650mm
Fastening		Pandrol Fastclip
Rail		CEN 60 E2
Infill concrete		According to detailed design (see also Preliminary Design report Ref [6]

APPENDIX C – DESIGN CLIP USED TO BUILD THE COMPUTER MODEL

KINGS CROSS ZONE W

RAMBOLL DESIGN CLIP 14b

28/08/15

KINGS CROSS W
SUBSTRUCTURE MARKUP

North-eastern corner of W1w shown with pilecaps cantilevering to avoid zone of loading Thameslink Tunnel.

RC GB02 1200 W x 2000 D ground beam to support corner column.

Allow for permanent retaining wall for level difference between external levels and B1 level along northern side of W1 Block. Enhancements for temporary construction condition to be developed by contractor.

Indicative RC ground beam location to support façade load above. Further coordination with architects required.

RC pile caps to be 2000mm deep.

RC columns centred on pile cap below U.N.O.

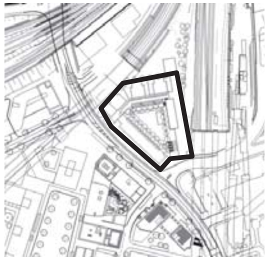
To avoid zone of loading tunnel, RC pilecap to be 2300mm deep beneath lift pits and parallel to Thameslink tunnel to cantilever.

In general minimum spacing c/c between 600dia RC piles 1800mm.

Transfer above W1 "peeled back façade". Refer to sketch 039-40.

Step in pile cap to accommodate lift pits.

RC pilecap 1800mm deep beyond step in cap.



KEY PLAN

General Notes:

1. Sketches are schematic only and not to scale
2. Sketches are preliminary only and are to be confirmed during design development.
3. Sketches should be read in conjunction with relevant design philosophy reports and architectural information.
4. All piles to be 600 diameter and to a depth of 31m U.N.O.
5. Pilecaps to be 1200mm deep U.N.O.
6. All ground beams to be 900mm wide x 1200mm deep U.N.O.
7. All columns to be centred on pilecaps U.N.O.
8. Pilecap and pile locations shown indicatively only at this stage. **Subject to change following updated architectural layouts**.

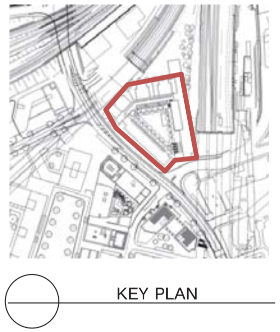
RAMBOLL

Project Title		Kings Cross W Zone	
Project N°		33832	
Sketch N°		S/SK058	
Title		SUBSTRUCTURE MARKUP	
Scale		NTS	
Eng:	Rev:	Date:	Checked
JH	P02	28/08/2015	WKC

KINGS CROSS W

LEVEL B1 STRUCTURAL MARKUP

circular columns in retail zone
with column heads at
transition with blade columns



KEY PLAN

General Notes:

1. Sketches are schematic only and not to scale
2. Sketches are preliminary only giving guidance to sizes and are to be confirmed during design development.
3. Sketches should be read in conjunction with relevant design philosophy reports and architectural information.
4. Location of movement joints representative of “peeled back façade” cantilever option. Movement joints for this option to be further developed but typically would follow façade line.

KEY

All column sizes in mm.

C1. 350 sq
C2. 450 sq
C3. 225 x 1050
C4. 225 x 1250
C5. 225 x 1600
C6. 225 x 1800
C7. 225 x 2100
C8. 400 x 850
C9. 400 x 1300
C10. 250 x 2500 (stability)
C11. 300 x 1350
C12. 300 x 2250
C13. 550sq OR 650 circ

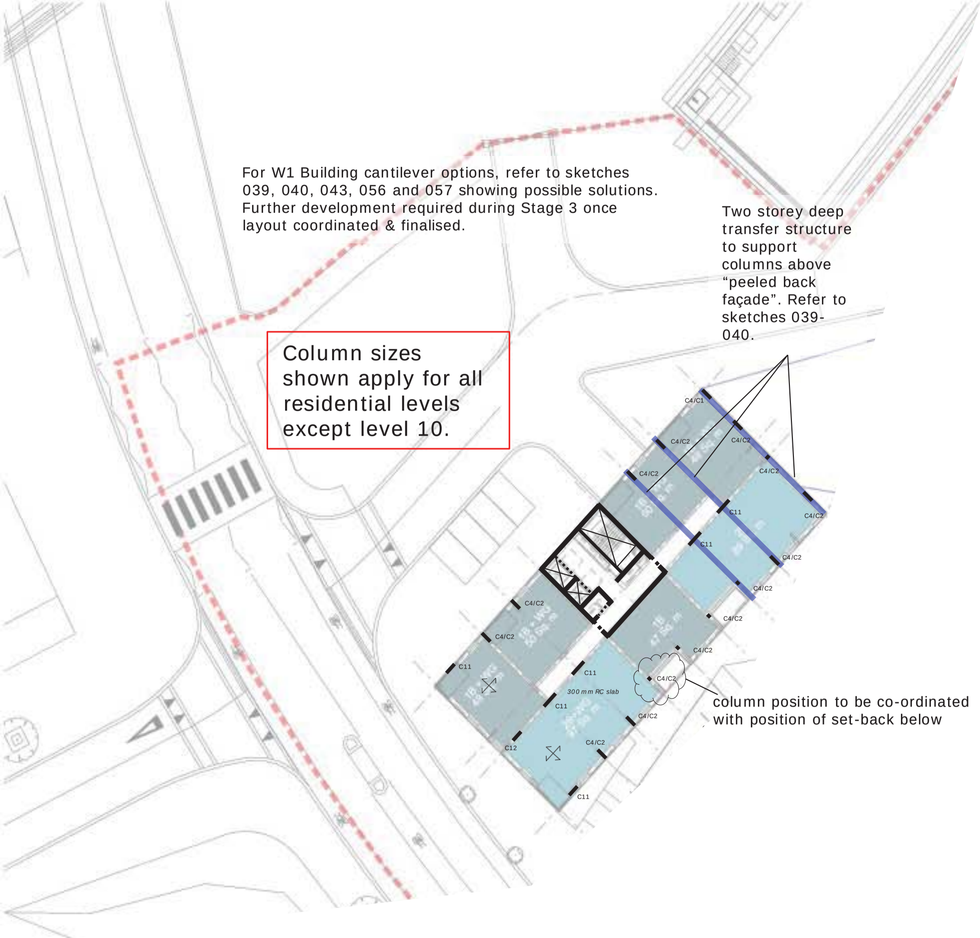
All core/stability walls to be taken as 300 mm wide, unless stated otherwise.

Movement joint
(above)

RAMBOLL

Project Title		Kings Cross W Zone	
Project N°		33832	
Sketch N°		S/SK048	
Title		LEVEL B1 STRUCTURAL MARKUP	
Scale		NTS	
Eng:	Rev:	Date:	Checked
JH	P03	28/08/2015	

KINGS CROSS W
LEVEL 01 STRUCTURAL MARKUP



For W1 Building cantilever options, refer to sketches 039, 040, 043, 056 and 057 showing possible solutions. Further development required during Stage 3 once layout coordinated & finalised.

Two storey deep transfer structure to support columns above "peeled back façade". Refer to sketches 039-040.

Column sizes shown apply for all residential levels except level 10.

column position to be co-ordinated with position of set-back below

W1 east as previous information

KEY PLAN

General Notes:

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KEY

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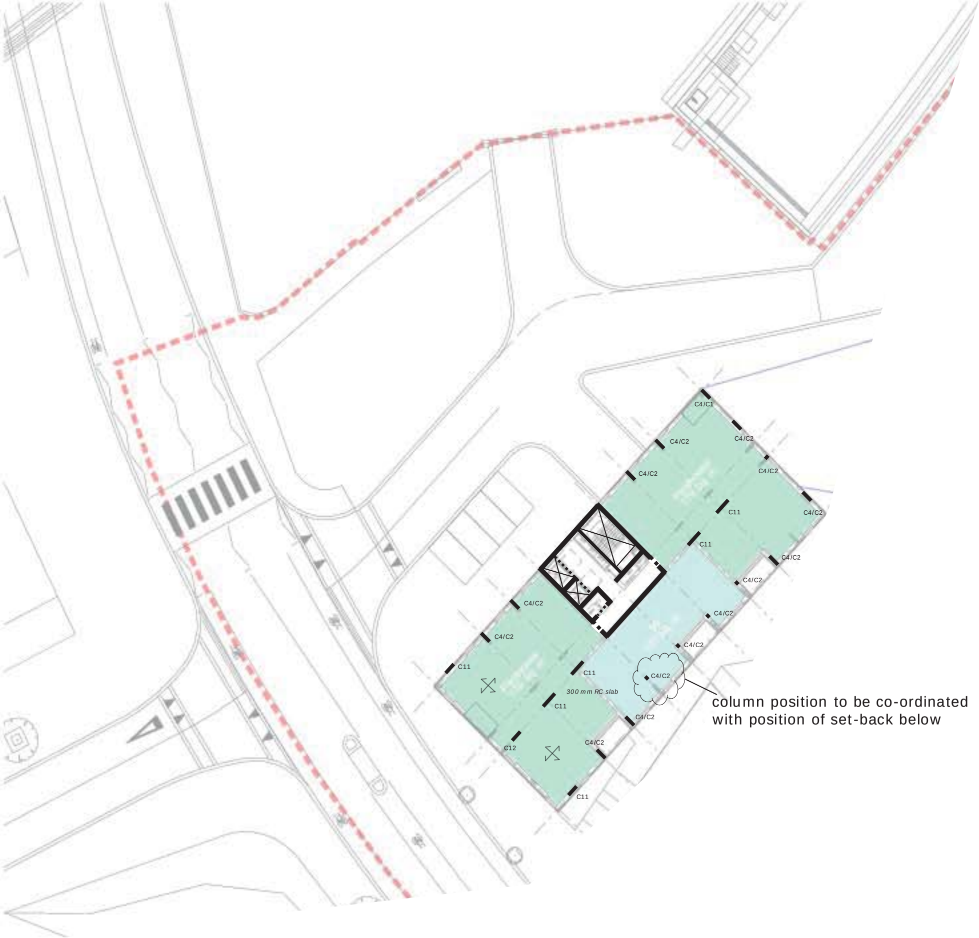
C7. 225 x 2100
C8. 400 x 850
C9. 400 x 1300
C10. 250 x 2500 (stability)
C11. 300 x 1350
C12. 300 x 2250

All core/stability walls to be taken as 300 mm wide, unless stated otherwise.

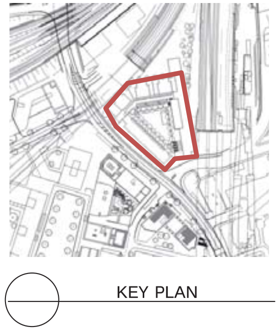
Project Title		Kings Cross W Zone	
Project N°		33832	
Sketch N°		S/SK050	
Title		LEVEL 01 STRUCTURAL MARKUP	
Scale		NTS	
Eng:	Rev:	Date:	Checked
JH	P03	28/08/2015	

KINGS CROSS W
LEVEL 10 STRUCTURAL MARKUP



column position to be co-ordinated with position of set-back below

W1 east as previous information



KEY PLAN

General Notes:

1. Sketches are schematic only and not to scale
2. Sketches are preliminary only giving guidance to sizes and are to be confirmed during design development.
3. Sketches should be read in conjunction with relevant design philosophy reports and architectural information.

KEY

All column sizes in mm.

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C2. 450 sq
C3. 225 x 1050
C4. 225 x 1250
C5. 225 x 1600
C6. 225 x 1800
C7. 225 x 2100
C8. 400 x 850
C9. 400 x 1300
C10. 250 x 2500 (stability)
C11. 300 x 1350
C12. 300 x 2250

All core/stability walls to be taken as 300 mm wide, unless stated otherwise.

RAMBOLL

Project Title		Kings Cross W Zone	
Project N°		33832	
Sketch N°		S/SK054	
Title		LEVEL 10 STRUCTURAL MARKUP	
Scale		NTS	
Eng:	Rev:	Date:	Checked
JH	P03	28/08/2015	

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