



Bakerloo line extension

Information for Developers
April 2021

MAYOR OF LONDON



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1 Introduction

- 1.1 This document provides guidance from Transport for London (TfL) relating to developments planned to commence or be completed prior to the commencement of construction of the Bakerloo line extension (BLE) and located within the Safeguarding Limits shown on the plans accompanying the Bakerloo line extension safeguarding Directions issued by the Secretary of State for Transport on 1 March 2021 (Directions).
- 1.2 Under Directions, local planning authorities (LPAs) are required to consult TfL before determining any application for planning permission for development wholly or partly within the Safeguarding Area (see paragraph 3 of the Directions). The Directions also specify that in certain cases applications do not have to be referred to TfL (see paragraph 4 of the Directions).
- 1.3 The purpose of the Directions is to protect the BLE by ensuring that any planning applications for development that may affect the BLE are considered by TfL and that the Secretary of State is given an opportunity to intervene if the LPA does not intend to follow the recommendation of TfL in determining the application. Examples of such developments include new construction on vacant sites, complete or partial reconstruction on existing or larger site area, enlargement of basements, increase in building height or density, new or modified foundations and changes of use involving increased sensitivity to noise and vibration, e.g. commercial to residential.
- 1.4 An applicant for planning permission ought to be able to demonstrate that the foundations of development proposals would not obstruct the route of the BLE tunnels or adversely impact on the construction, design or operation of the tunnels, stations and other infrastructure related to the BLE. Developments should also be designed to avoid TfL incurring any excessive additional cost in constructing or operating the BLE. If an applicant cannot satisfy TfL on these matters, then TfL is likely to recommend that planning permission is refused or granted subject to a condition or conditions (and/or a planning obligation) that protects the BLE.
- 1.5 New developments should be designed to accommodate the construction and operation of the BLE. The potential effects on developments include ground movements during construction and noise and vibration during both construction and railway operation. The railway is designed to achieve a 120-year design life that may well exceed the design life of building projects. Developers' designs must also take into account and demonstrate that the integrity and operability of the BLE assets will not be prejudiced as a consequence of the demolition of the development in the future.
- 1.6 As part of the consultation process on planning applications under the Directions, TfL can:
 - a) Make no comment
 - b) Recommend that the LPA place conditions on a planning permission to ensure that the delivery and operation of the BLE are not prejudiced (see further Section 6 below)

c) Recommend that the application be refused

- 1.7 Guidance on the BLE design assumptions is set out in this document. They aim to assist developers in ensuring that new development does not affect the construction or operation of the BLE and that the development itself is not unduly affected by the construction and operation of the BLE.
- 1.8 TfL welcomes early dialogue with developers about the design of developments and upon planning conditions that might be appropriate in respect of them. Development agreements may be appropriate in some circumstances.
- 1.9 The Directions do not require TfL to be consulted prior to permitted development under the Town and Country Planning (General Development) (England) Order 2015 being carried out. However, TfL would welcome approaches from developers for such works where it is considered there could be an impact on the BLE. The LPAs work with TfL and should be able to advise, where development proposals are not referable to the Mayor and TfL, of the need or otherwise to engage with TfL. Nonetheless, for the avoidance of doubt, if you have general queries about the BLE Safeguarded Area please refer to railwaysearches@tfl.gov.uk. To make enquiries about any other aspect of the BLE please contact ble@tfl.gov.uk.

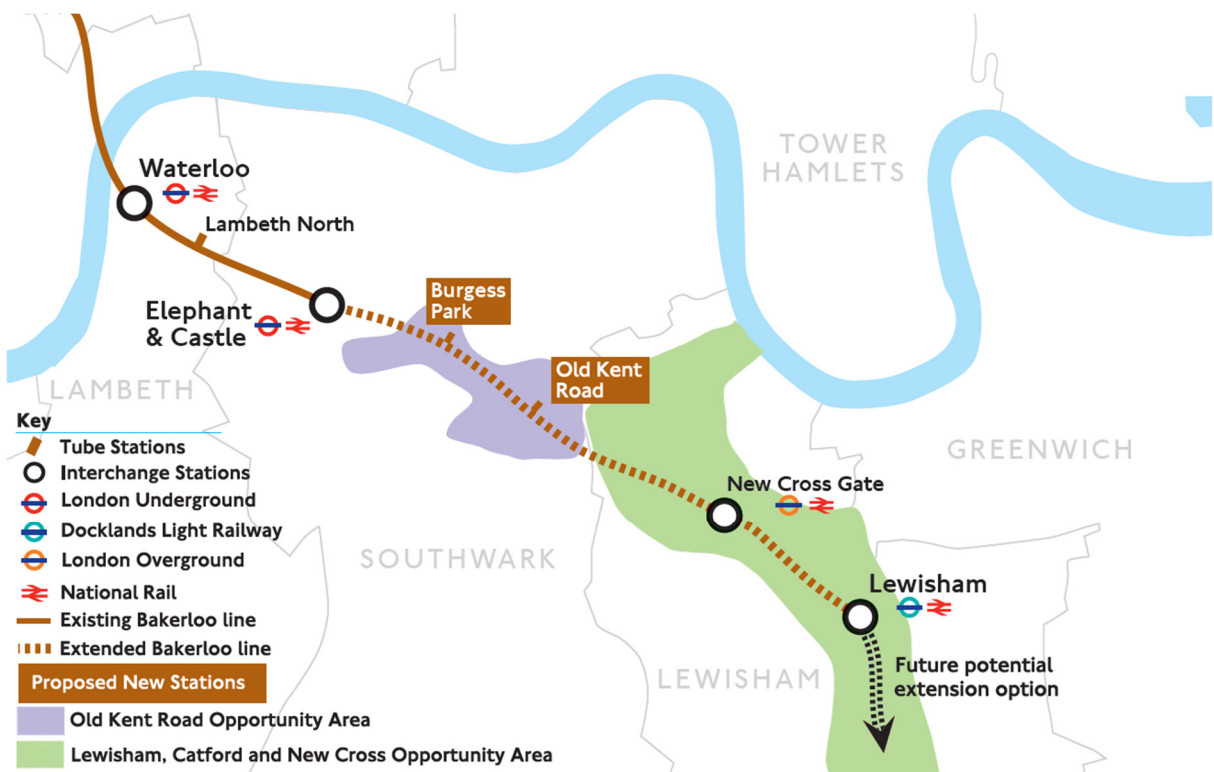


Figure 1: 2019 Consulted Route Proposal to Lewisham via Old Kent Road and New Cross Gate

2 General Information

2.1 Tunnel size

The BLE will be building two running tunnels along the route, with cross passages located at regular intervals. These will be located within the Safeguarded Area.

The excavated diameter of the BLE running tunnels should be taken as 6m, with an internal diameter of 5m (see Figure 2).

The diameter of cross passages, station platform escalators, ventilation and other tunnels and shafts varies. The location and size of these tunnels and shafts will be subject to further design development. The developer should contact the BLE Safeguarding Manager for further advice on this issue, details are provided in Section 5 of this document.

2.2 Tunnel exclusion and construction tolerance zones

Depending on the stage of design development at the time of the request, details of the BLE tunnels and other infrastructure will be provided by the BLE Safeguarding Manager. It should be noted, however, that the BLE infrastructure could be in any position both horizontally and vertically within the Safeguarded Area.

The following criteria will apply to the BLE tunnels in particular locations:

- a) Developers should note that an “Exclusion Zone” will exist around all tunnels. For each running tunnel, see Figure 2, this Exclusion Zone (13m wide and 16m high) corresponds to the area of sub-soil that BLE would seek to acquire under the terms of the enabling Transport and Works Act Order (in effect, the instrument by which planning consent is given). The Exclusion Zone is required to safely construct, operate and maintain the BLE. Foundations and temporary works may not encroach into the Exclusion Zone unless otherwise agreed with TfL. The Exclusion Zone includes a 0.5m tunnel “Construction Tolerance Zone” giving a total of 3.5m both sides and to the bottom of the tunnels and 6.5m above the tunnels. Special forms of foundation construction (e.g. widely spaced heavily loaded under-reamed deep piles) may require a greater vertical separation. In these cases, the developer will need to assess the minimum separation that will ensure the construction or operation of BLE nor the development itself is prejudiced.
- b) TfL will retain the flexibility to move the tunnels 3m in either direction horizontally and a minimum of 1m vertically upwards. This is referred to as the “Alignment Adjustment Zone” and the design of any new development should take account of this possible deviation. Developers should discuss this with the BLE Safeguarding Manager. The Alignment Adjustment Zone is required to retain flexibility to amend the BLE alignment within the Safeguarded Area to avoid potential obstructions or other alignment constraints as the tunnel design evolves. Figure 2 identifies these zones on an indicative section, showing one tunnel.

- c) The developer must make adequate allowance for the construction tolerance of their proposed development foundations in determining their proximity to the BLE tunnels.
- d) Depending on the stage of design development, in certain locations there may be scope for discussing the extent to which paragraphs a to c above apply. The BLE Safeguarding Manager will advise the developer accordingly.

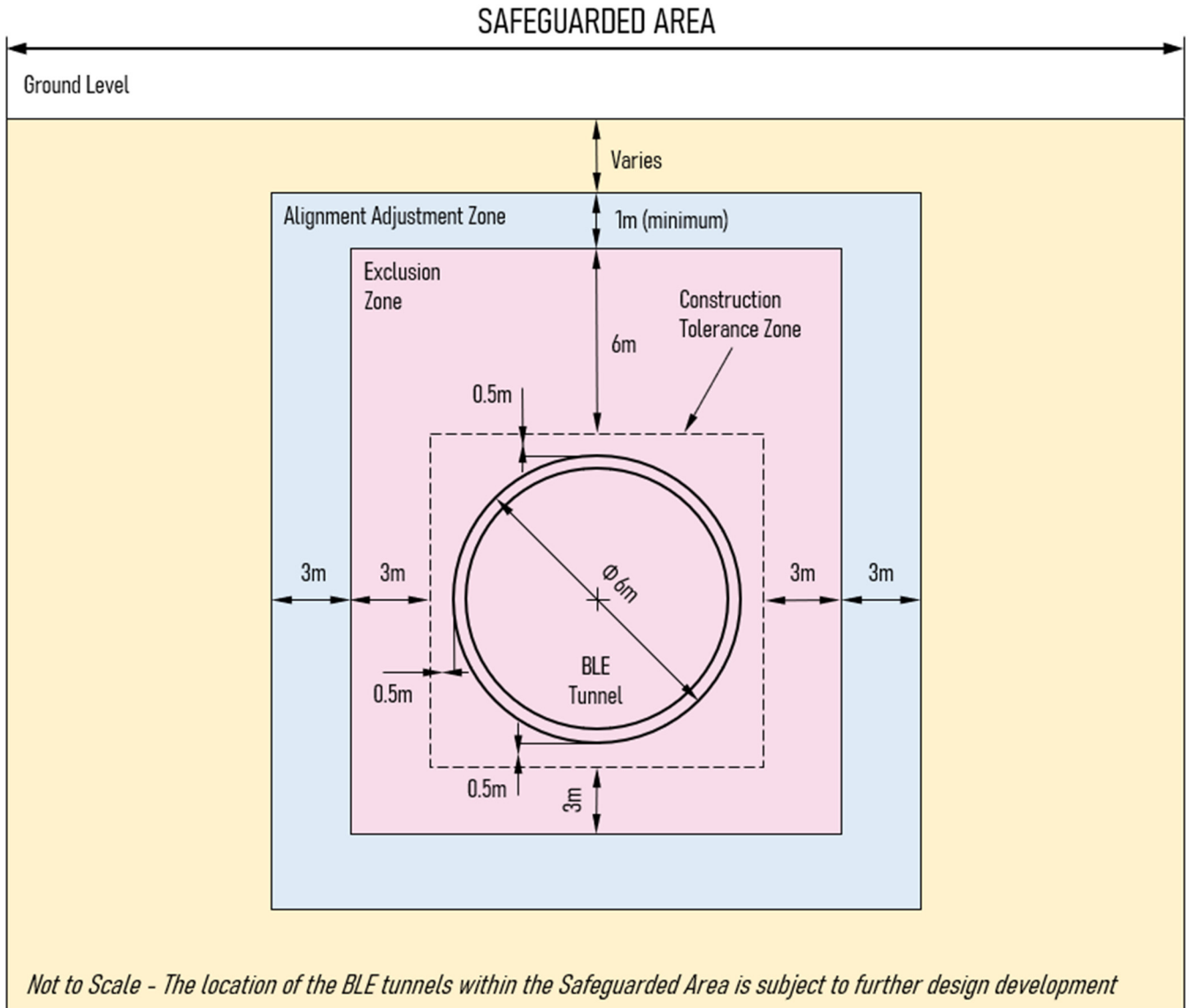


Figure 2: Indicative cross section showing a BLE running tunnel, Exclusion Zone and Alignment Adjustment Zone

2.3 Stations, shafts and other areas of surface interest.

The BLE will also be constructing buried station box structures and ventilation and emergency services access shafts at several locations. Developers will be required to consider the impact of their proposals on these station box structures and shafts in a similar manner to the BLE tunnels, especially with regards to foundations and temporary works. The developer should seek advice from the BLE Safeguarding Manager (refer to Section 5 for details) regarding the particular constraints imposed

by these structures. This includes constraints linked to BLE-related emergency access/egress and ventilation.

The developer must make adequate allowance for the construction tolerance of their proposed development foundations and/or temporary works in determining their proximity to the BLE station box structures and shafts.

2.4 Loads from development foundations

Development foundations must be designed so that changes in stress in the future tunnel linings do not exceed acceptable levels. Changes in stress due to foundations or basements shall be considered.

In general, this will be achieved if the overall loading imposed on the tunnels:

- a) Does not exceed the existing ground overburden plus the loading from any existing development (as would be the case for redevelopment of an existing site)
- b) Does not exceed the existing ground overburden plus 50kN/m² imposed at ground level over the footprint of the development (as would be the case in development of a vacant site)

The BLE tunnels will be designed to account for existing loads.

In the assessment of overall loading, the reduction in overburden arising from provision of a new basement, tunnel or other subsurface construction beneath the development can be taken into account to offset increased surcharge from the development.

3 Ground Movement

- 3.1 Construction of the BLE portal, tunnels, shafts and station boxes has the potential to cause movement of the ground adjacent to these structures. The foundations of new developments (or modification to the foundations or basements of an existing development) should therefore be designed so that damage to the development from this settlement does not exceed acceptable levels.
- 3.2 TfL uses a methodology to calculate ground movement which has been used on numerous projects (e.g. Jubilee Line Extension, Channel Tunnel Rail Link (HS1), Crossrail) and has been found to be a reliable approach to estimating ground movement. The method TfL uses to calculate ground movement is described in Appendix A. The developer may wish to use the same methodology, although TfL cannot accept any responsibility for its use, and use of the methodology should not be taken as guaranteeing that TfL will recommend a planning application is granted (or planning conditions are not required).
- 3.3 The face losses from BLE tunnelling will not exceed 1.2% for 6m diameter running tunnels, this value is based on back-analysed results from Crossrail. For all other tunnels, including those constructed by SCL (sprayed concrete linings), percentage face losses from tunnelling will not exceed 1.5%. These face loss values of 1.2% (running tunnels) and 1.5% (all other tunnels) should be used in any ground movement assessments.

4 Operational Noise and Vibration

- 4.1 As discussed further in Section 5, TfL may recommend the imposition of planning conditions to a planning permission. These conditions may in turn require the provision of adequate assessments in relation to the interface between operational noise and vibration from the BLE and the proposed development, insofar as this information has not been provided at the application stage. [Developers should satisfy themselves at the application stage that their proposed developments will be capable of proceeding subject to such conditions].
- 4.2 The operation of Bakerloo line trains has the potential to cause vibration to be transmitted from the tunnels to the foundations of local buildings which could then be re-radiated as groundborne noise within the building. The potential for this effect is higher when the foundations are in close proximity to the tunnels.
- 4.3 The reason for the planning conditions will be to ensure that the proposals for development (or modification to the foundations or basements of an existing development) within the Safeguarded Area have foundations which are compatible with the levels of vibration and groundborne noise generated within the building or nearby structures from the operation of Bakerloo line trains.
- 4.4 The developer should use the information in Appendix B, as developed for the Crossrail 2 project, to predict the levels of vibration and groundborne noise in their development and ensure any necessary mitigation is in place in order to allow for the discharge of the relevant condition.. TfL cannot accept any responsibility for the use of this information, and its use should not be taken as guaranteeing that TfL will advise the LPA that the terms of the relevant planning condition have been met.
- 4.5 In accordance with Appendix B:
- The developer should use the assumption that the BLE will adopt an operational track system with an equivalent performance to the high-performance standard track used by Crossrail (Appendix B gives details).
- The levels of vibration at the tunnel wall caused by the passage of a single train travelling at both 100 km/h and 80 km/h for the BLE has been taken as equivalent to that modelled for the Crossrail 2 project. These are presented in Table 1 and Table 2 and graphically in Figure 1 to Figure 4 in Appendix B.
- 4.6 Details of this noise and vibration assessment, and any necessary mitigation measures, should be clearly set out in a noise and vibration report prepared by a suitably competent and experienced acoustic consultant with demonstrable experience of assessing noise and vibration from the operation of underground rail systems. This report should be submitted to the LPA as part of the application to discharge the planning condition regarding the BLE, and the LPA will in turn refer it to the BLE project team, for consideration.
- 4.7 The BLE Safeguarding Manager will advise the developer of any issues related to the assessment or the building design and liaise with the developer to resolve them. The

developer may have to submit further information if the report submitted is not satisfactory. Once the BLE Safeguarding Manager is satisfied with the information, TfL will be able to advise the LPA. It has no objection to a planning condition being discharged.

- 4.8 The developer is strongly recommended to enter into early discussions with the BLE Safeguarding Manager about their development proposals prior to finalisation and submission of the noise and vibration report.

Building	Level/Measure
Residential buildings	35dB L _{Amax,F}
Offices	40dB L _{Amax,F}
Theatres	25dB L _{Amax,F}
Hotels	40dB L _{Amax,F}
Large auditoria/concert halls	25dB L _{Amax,F}
Sound recording studios	30dB L _{Amax,F}
Places of meeting for religious worship ¹	35dB L _{Amax,F}
Courts, lecture theatres	35dB L _{Amax,F}
Small auditoria/halls	35dB L _{Amax,F}
Hospitals, laboratories	40dB L _{Amax,F}
Libraries	40dB L _{Amax,F}

Table 1: Operational Groundborne Noise Design Aims

Notes:

1. Meaning a place the principal use of which is for people to come together as a congregation to worship God or do reverence to a deity.

In the Absences of Appreciable Existing Levels of Vibration		Appreciable Existing Levels of Vibration ^{1 2}
VDV ms ^{-1.75} Daytime (07:00 – 23:00)	VDV ms ^{-1.75} Night-time (23:00 – 07:00)	% Increase in VDV
0.31	0.18	40

Table 2: Operational Vibration Criteria

Notes:

1. Highest impact category used, daytime or night-time.
 2. There is an appreciable existing level of vibration where daytime and night-time vibration dose values (VDVs) exceed 0.22 ms^{-1.75} and 0.13 ms^{-1.75} respectively.

5 Engagement with the Bakerloo line extension

- 5.1 Developers are encouraged to engage with TfL prior to submission of a planning application to the LPA (or an application for a lawful development certificate in the case of permitted development), to maximise opportunity for understanding and consideration of project interface constraints and opportunities, and in the case of planning applications, the conditions which TfL may seek to impose on the development in order to manage the impact on, and of, the construction and operation of the BLE.
- 5.2 The principal point of contact for BLE Safeguarding matters is:
- BLE@tfl.gov.uk
- 5.3 Developers should submit reports and drawings demonstrating their compliance with this guidance document. Such reports and drawings, when reviewed and accepted by the BLE Safeguarding Manager, will enable TfL to confirm it does not intend to recommend refusal and, if relevant, recommend any planning conditions for the development under the terms of the Directions.
- 5.4 In some instances, a development or other legal agreement between the developer and TfL may be required. It might also be appropriate for planning obligations to include provisions necessary to protect the delivery of the BLE as a pre-requisite to planning permission being granted.
- 5.5 TfL reserves the right to charge developers for time and resource utilised in assessing development proposals, particularly where specialist engineering and legal resources have to be commissioned to advise. If charges are anticipated, these will be advised to the developer before these costs are incurred. The developer will be expected to provide its invoicing instructions and a commitment to reimburse TfL before costs are expended.
- 5.6 TfL recommends that evidence is presented in a structured format such as a Conceptual Design Submission (CDS) using the approach set out in Appendix A for building damage assessment calculations and the approach for noise and vibration set out in Appendix B (though, as stated above, TfL does not take any responsibility for the use of those appendices, and such use should not be taken as guaranteeing that a recommendation will not be made against the development). This will allow TfL to examine the assumptions and calculations that have been undertaken in a consistent manner across the route. If an alternative approach for the calculations are submitted, TfL reserves the right to charge developers for time and resources utilised in assessing development proposals, particularly where specialist engineering and / or legal resources have to be commissioned. If charges are anticipated, then these will be advised to the developer before the costs are incurred. The developer will be expected to provide its invoicing instructions and a commitment to reimburse TfL before costs are expended.

TfL recommends that the CDS should follow the layout and sub-headings as set out below:

- a) Executive Summary.
- b) Introduction, setting out objectives:
 - That the future construction or operation of the BLE is not prejudiced by the proposed building.
 - That the building itself is not adversely affected to an unacceptable degree by the construction or operation of the BLE.
 - Stating compliance with terms of a development agreement (if applicable).
- c) Overview, outlining:
 - The nature of the development.
 - Proximity to BLE infrastructure.
 - Assumptions for tunnel diameter, clearance requirements and exclusion zones, volume loss and noise & vibration assessment and other criteria as set out in this document.
- d) The Parties, including contacts, roles and responsibilities.
- e) Outline Project Programme, including key milestone dates (accuracy commensurate with knowledge at planning stage of development).
- f) Summary of assumptions on existing site conditions, to include:
 - Compiled assumptions on ground conditions, groundwater and ground contamination (if appropriate) with at least one bore hole log.
 - Details substantiated by desk top assessment or intrusive surveys as appropriate, supplied by the developer's design representatives.
- g) Effects of BLE construction on the proposed development, to include:
 - Summary of predicted settlement damage assessment (using method in this document for shallow foundations, if applicable – calculations to be appended) and to include a Category 2 check.
 - Summary of noise & vibration assessment (using method prescribed).
- h) Standards and References.
- i) Quality Control sheet, signed by compiler, checker and director (or senior manager).
- j) Appendices:
 - The drawings to include plans, cross sections and long sections as appropriate, showing the relationship between the development and the proposed position of the BLE as advised by the BLE Safeguarding Manger.

- 5.7 The developer's design should be submitted using the London Survey Grid format, converted from Ordnance Survey National Grid. LSG Height Datum (LSGH) shall be used. The datum level is set at approximately 100m below OS datum at Newlyn.
- 5.8 Provision of the required reports can be phased if this suits the developer's design programme and TfL will recommend part discharge of planning conditions as appropriate.
- 5.9 Reports should be in digital format sent by email. File sharing via methods such as "We Transfer" is not acceptable. A hard copy may be required.
- 5.10 On completion of construction, as-constructed drawings of the foundations (including schedule of pile toe levels), left in place temporary works and site plan, all in digital format should be provided to TfL. Details of work above ground level are not usually required.
- 5.11 It would be helpful if the developer contacts the BLE Safeguarding Manager if it is decided not to proceed with development, or the start date is delayed by over 6 months from that originally advised.

6 Bakerloo line extension Planning Conditions

- 6.1 The Directions require that planning applications to which they apply are referred by the LPA to TfL for its consideration. TfL's recommendation in response to the LPA under the terms of the Directions could be:
- a) No comments provided
 - b) That the application should be refused
 - c) That a condition in the form set out below (or one which is in substantially similar form) should be imposed
 - d) That another condition or conditions should be imposed on the permission
- 6.2 The condition below is intended to provide guidance to developers on the typical form of a condition which may be recommended. As indicated above, a bespoke, condition or conditions may be more appropriate depending on the details of any particular development. The condition below should not be confused with the condition for exempt applications under paragraph 4(c) of the Directions.

Bakerloo Line Extension Standard Condition (B1)

None of the development hereby permitted shall be commenced until detailed design and construction method statements for all of the ground floor structures, foundations and basements and for any other structures or works below ground level, including piling, any other temporary or permanent installations and ground investigations have been submitted to and approved in writing by the Local Planning Authority following consultation with Transport for London by the Local Planning Authority, which:

- (i) Accommodate the proposed location of the Bakerloo line extension tunnels, structures, infrastructure (including stations and station infrastructure) and any temporary works in the vicinity of the site*
- (ii) Accommodate ground movement arising from the construction thereof*
- (iii) Mitigate the effects of noise and vibration arising from the operation of the Bakerloo line extension within its tunnels and other structures*

The development shall be carried out in all respects in accordance with the approved design and method statements. All structures, foundations, installations and works comprised within the development hereby permitted which are required by this condition shall be completed, in their entirety, before any part of the building[s] hereby permitted is/are occupied or is otherwise opened for public use. No alteration to these aspects of the development shall take place without the approval of the Local Planning Authority in consultation with Transport for London.

Informative:

Applicants should refer to the Bakerloo line extension Information for Developers available at <https://tfl.gov.uk/corporate/about-tfl/how-we-work/planning-for-the-future/bakerloo-line-extension>. TfL will provide further guidance in relation to the proposed location of the Bakerloo line extension structures and tunnels, ground movement arising from the construction of the tunnels and noise and vibration arising from the use of the tunnels. Applicants are encouraged to contact the Bakerloo line extension Safeguarding Manager in the course of preparing detailed design and method statements.

- 6.3 An LPA may accept a planning obligation under section 106 Town and Country Planning Act 1990 to secure the same or similar measures as those set out in the condition. TfL should be involved in discussions about the content of the relevant proposed provisions in a S106 obligation, and may need to be a party to any section 106 agreement.
- 6.4 Where development interface risks have been identified which require managing during the design and/or implementation phase of a development TfL may wish to enter into a pre-commencement “Development Agreement” (DA) with the applicant / developer in order to give certainty to both parties. The DA may include, but not be limited to, provisions covering: agreement of schedules of works; mitigation measures; working and other protocols; ground movement and settlement impact; noise and vibration assessment; potential and cumulative impact on third party assets; access arrangements; consultation and logistic planning; health and safety; and phasing of development implementation, or other conditions as appropriate.

Appendix A

Prediction of Ground Movements and Associated Building Damage due to Bored Tunnelling

1 Introduction

- 1.1 The purpose of this document is to present a method of assessing the potential damage to masonry buildings due to tunnelling.
- 1.2 In assessing building damage due to tunnel construction, the Bakerloo Line Extension Safeguarding Manager will use a staged process, with increasing detail included at each phase of assessment, to eliminate building and structures from further consideration. The calculation procedure described in this document covers the phase 2 assessment of settlements and building damage due to tunnel construction. A simplified analysis for a plane strain conditions are assumed. More complex three-dimensional cases, as would exist at station and shaft locations, are not covered. However, for the majority of cases where only running tunnels are present, the two-dimensional idealisation will be adequate.
- 1.3 The method adopted essentially uses an empirical procedure (based on field measurements) to determine ground movements at foundation level, assuming 'greenfield' conditions, i.e. ignoring the presence of the building and the ground above foundation level. It is then assumed that the building follows the ground (i.e. it has negligible stiffness) and hence the distortions and consequently the strains in the building can be calculated. A risk or damage assessment is made using the criteria defined by Burland and Wroth (1974) and the classification presented by Burland et al (1977).
- 1.4 The method of predicting ground movements is applicable to all bored horizontal tunnels (at inclinations of up to 30° to the horizontal). The procedure for calculating building strains is only relevant to buildings on shallow foundations (which may include a basement), and the method of assessment of potential damage is only applicable to masonry structures.

2 Procedure for Predicting Movements due to Tunnelling

2.1 Vertical settlement

Initially, the case of a single tunnel will be considered. The procedure adopted generally follows that outlined by O'Reilly and New (1982) and extended by New and O'Reilly (1991). Figure 1 below shows a tunnel of excavated diameter D with its axis at depth z below ground level (it can be assumed that this procedure is also applicable to non-circular tunnels).

In the context of predicting settlement damage to buildings, ground level is taken as foundation level. Construction of the tunnel results in ground movements with a settlement trough developing above the tunnel. Analysis of a considerable number of case records has demonstrated that the settlement trough is well described by a Gaussian distribution curve as:

$$S_v = S_{\max} \exp\left[\frac{-y^2}{2i^2}\right]$$

where S_v is the vertical settlement,

S_{\max} is the maximum vertical settlement on the tunnel centre line,

y is the horizontal distance from the centre line, and

i is the trough width parameter and is the horizontal distance to the point of inflexion on the settlement trough.

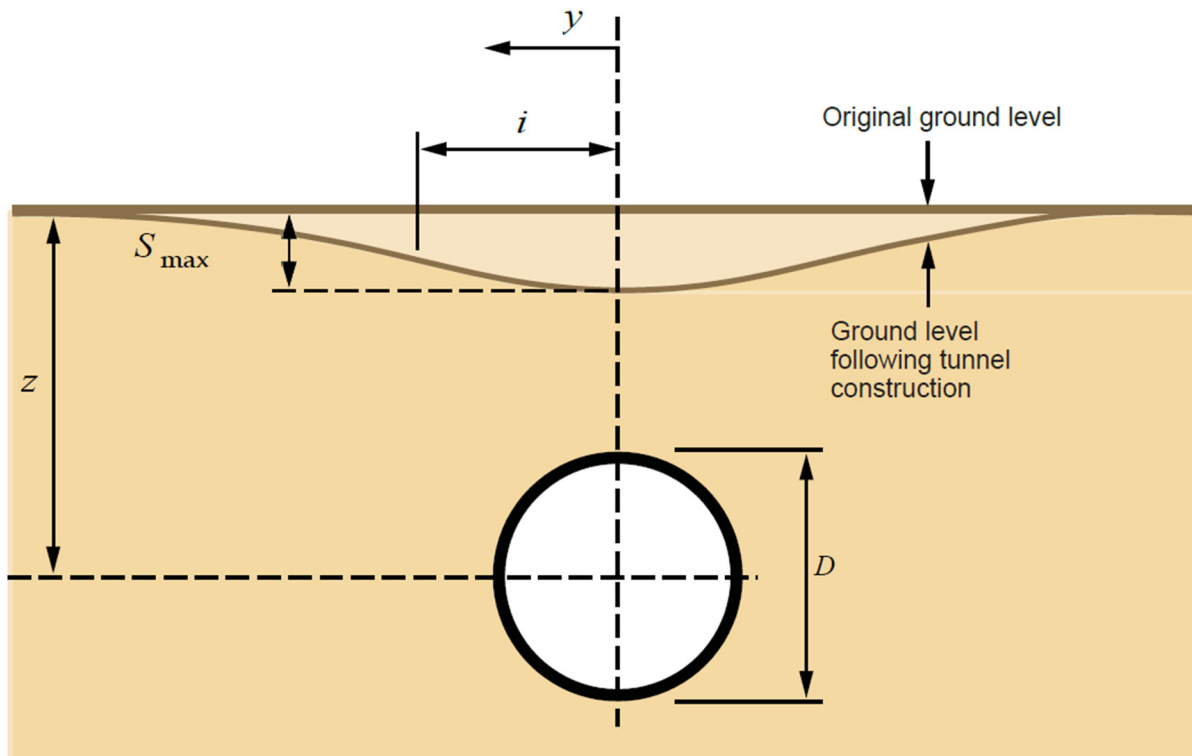


Figure 1: Cross section showing tunnel geometry

The volume of the settlement trough (per metre length of tunnel), V_s , can be evaluated by integrating Equation 1 to give:

$$V_s = \sqrt{2\pi}iS_{\max}$$

The volume loss is usually expressed as a fraction, V_l , of the excavated area of the tunnel, i.e. for a circular tunnel:

$$V_s = V_l \frac{\pi D^2}{4}$$

For non-circular or inclined tunnels, the area of the tunnel intersected by a vertical plane should replace the term $\pi D^2/4$ in Equation 3. O'Reilly and New (1982) collated data from many tunnel construction projects and were able to show that for tunnels in London Clay V_l is likely to be in the range one to three per cent.

The selection of appropriate values of volume loss depends on the construction method envisaged and on the ground conditions.

O'Reilly and New also correlated data of observed settlement troughs to show that the trough width parameters i was a reasonable linear function of the depth z and independent of tunnel construction method. It can be assumed that the simple approximate form

$$i = Kz$$

can be adopted. Values of K for tunnels in clay (cohesive soil) and sands or gravels (granular soils) are taken as approximately 0.5 and 0.25 respectively. The choice of an appropriate value of K will often require some judgement, since it depends on whether the ground between the tunnel and the foundation being considered is primarily cohesive or granular. Equations 1 to 4 can be combined to give the predicted vertical settlements, as;

$$S_v = \frac{V_s}{\sqrt{2\pi}Kz} \exp\left[\frac{-y^2}{2K^2z^2}\right]$$

2.2 Horizontal movements

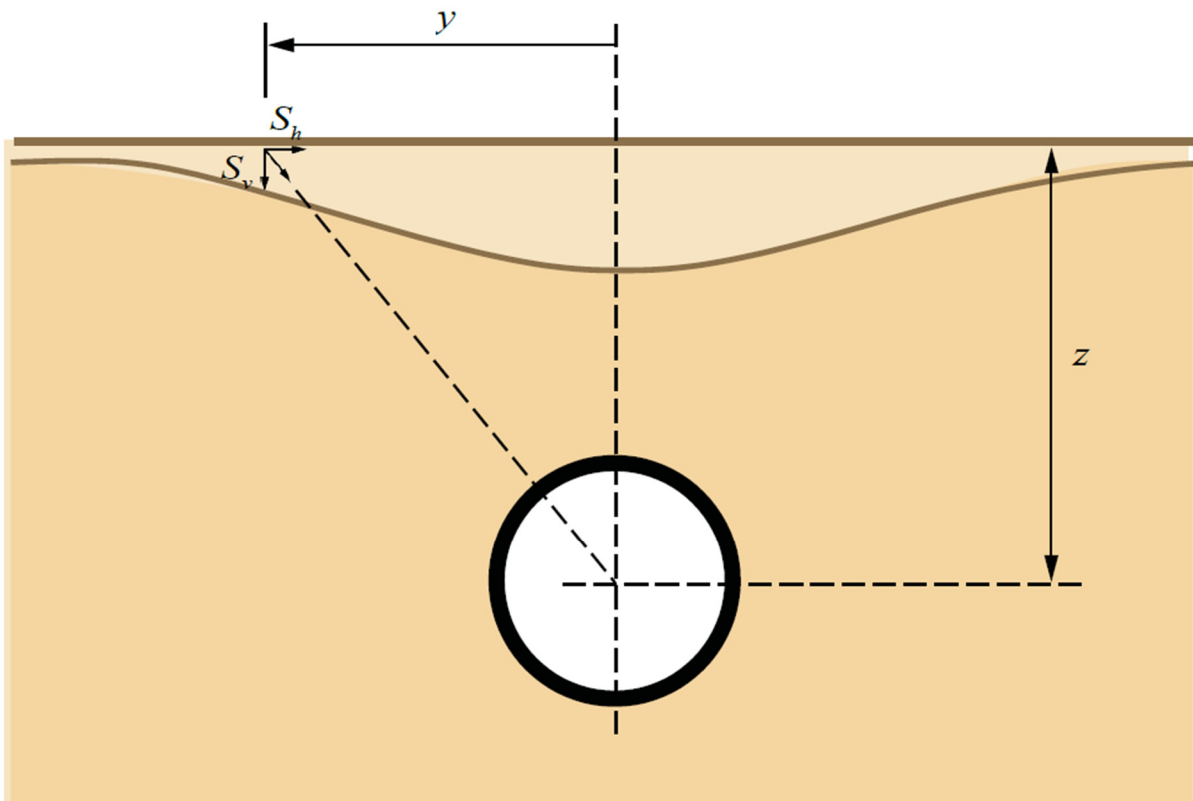


Figure 2: Surface movement above a tunnel

Building damage can also result from horizontal tensile strains, and therefore a prediction of horizontal movement is required. There are few case histories where horizontal movements have been measured, but the data that exist show reasonable agreement with the assumption of O'Reilly and New (1982) that the resultant vectors of ground movement are directed towards the tunnel axis. As shown on Figure 2 above, the vector of ground movement has vertical and horizontal components S_v and S_h respectively. Assuming that the vector is directed towards the tunnel axis, then:

$$S_h = \frac{y}{z} S_v$$

which allows a simple assessment of horizontal movement. Equation 6 can be rewritten as:

$$S_h = \frac{V_s y}{\sqrt{2\pi K z^2}} \exp\left[\frac{-y^2}{2K^2 z^2}\right]$$

Horizontal strain can be determined by differentiating Equation 7 with respect to y , which gives:

$$\epsilon_h = \frac{dS_h}{dy} = \frac{V_s}{\sqrt{2\pi K z^2}} \exp\left[\frac{-y^2}{2K^2 z^2}\right] \left\{1 - \frac{y^2}{K^2 z^2}\right\}$$

i.e.

$$\epsilon_h = \frac{S_h}{y} \left[1 - \frac{y^2}{K^2 z^2} \right] = \frac{S_v}{z} \left[1 - \frac{y^2}{K^2 z^2} \right]$$

it is relevant to note that the vertical strain is given by:

$$\epsilon_v = \frac{dS_v}{dz} = \frac{V_s}{\sqrt{2\pi} K z^2} \exp \left[\frac{-y^2}{2K^2 z^2} \right] \left\{ \frac{y^2}{K^2 z^2} - 1 \right\}$$

i.e.

$$\epsilon_v = \frac{S_v}{z} \left[1 - \frac{y^2}{K^2 z^2} \right] = -\epsilon_h$$

Since $\epsilon_h + \epsilon_v = 0$ a constant volume (i.e. undrained) condition is implied, which is generally found during tunnel construction in clay. For tunnels in sands or gravels, some bulking (dilation) of the ground might be expected, and Equations 6 to 8 are likely to over predict horizontal movements and strains.

Figure 3 below shows the relation between the vertical settlement trough, the horizontal movements and horizontal strains occurring at ground level.

In the region, $i > y > -i$, horizontal strains are compressive. At the points of inflexion $y = \pm i$, the horizontal movements are the greatest, and the horizontal strain is zero. For $i < y < -i$, the horizontal strains are tensile.

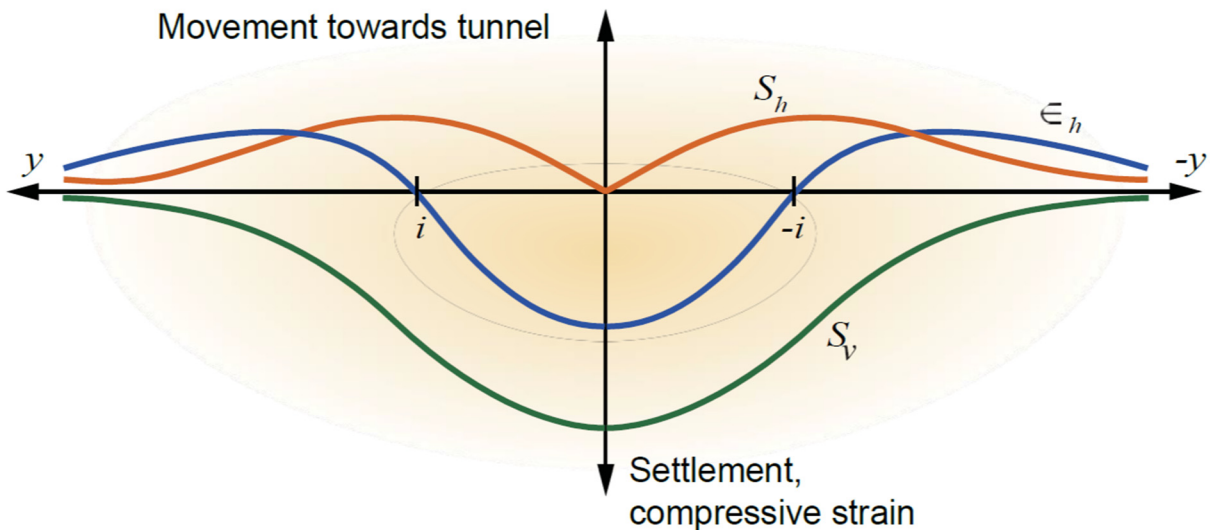


Figure 3: Distribution of vertical and horizontal movements and horizontal strains above a tunnel

2.3 Multiple tunnels

It is assumed that superposition can be applied using all the above equations. It is usually simplest to calculate movements and strains relative to a fixed reference point at the ground surface, and often the edge of a building is chosen.

Such a case is illustrated on Figure 4 below.

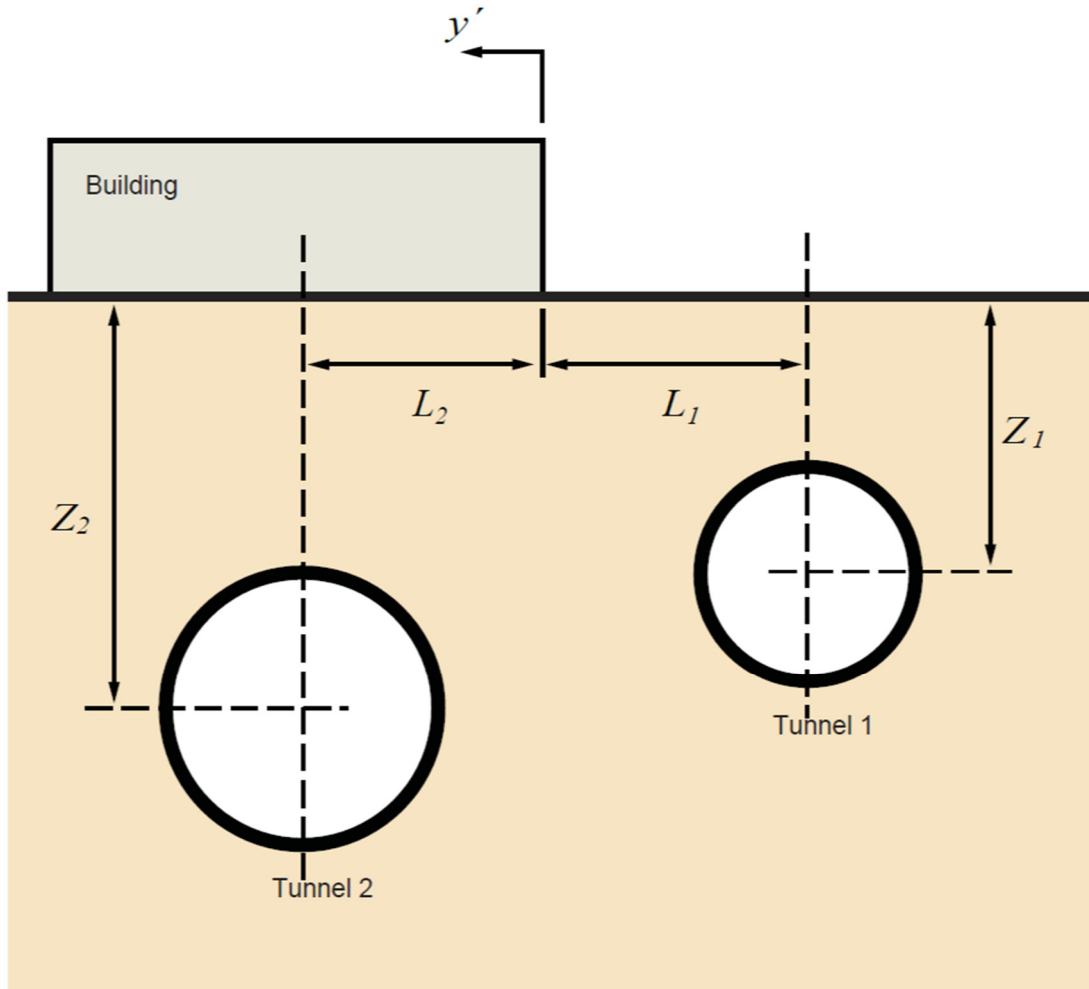


Figure 4: Cross section showing typical geometry with twin tunnels passing beneath a building

For Tunnel 1, Equations 1 to 9 can all be used as required by substituting $z = z_1$ and $y = y' + L_1$ in the equations. Similarly, for Tunnel 2, $z = z_1$ and $y = y' - L_2$ should be substituted. Total movements and strains are then found by summation, for example:

$$S_v = S_{v1} + S_{v2}$$

i.e.

$$S_v = \frac{1}{\sqrt{2\pi}} \left\{ \frac{V_{s1}}{K_1 z_1} \exp \left[\frac{-(y' + L_1)^2}{2K_1^2 z_1^2} \right] + \frac{V_{s2}}{K_2 z_2} \exp \left[\frac{-(y' + L_2)^2}{2K_2^2 z_2^2} \right] \right\}$$

Different tunnel diameters or volume loss parameters can be easily taken into account.

The points of inflexion of the combined settlement trough are required for the assessment of building damage. For the settlement trough above a single tunnel, the slope is given by:

$$\frac{dS_v}{dy} = \frac{-V_s y}{\sqrt{2\pi} K^3 z^3} \exp\left[\frac{-y^2}{2K^2 z^2}\right]$$

and the curvature is given by

$$\frac{d^2 S_v}{dy^2} = \frac{V_s}{\sqrt{2\pi} K^3 z^3} \exp\left[\frac{-y^2}{2K^2 z^2}\right] \left\{ \frac{y^2}{K^2 z^2} - 1 \right\}$$

The curvature of the settlement profile due to multiple tunnels can be determined by summation of the curvatures due to individual tunnels (a change in the sign of curvature occurs at a point of inflexion).

Alternative methods of calculating ground movements due to tunnel excavation such as New and Bowers (1994) may be appropriate particularly for cases where structures are within one diameter of any tunnel.

3 Building Strains

3.1 Relevant building dimensions

It is necessary to define the relevant height and length of the building. A typical situation that might exist is shown on Figure 5. The height is taken as the height from foundation level to the eaves. It is assumed that a building can be considered separately either side of a point of inflexion, i.e. points of inflexion of the surface settlement profile will be used to divide the building. For example, building lengths L_h and L_s should be used respectively when assessing building damage in the hogging and sagging zones. The length of building will not be considered beyond the limit of the settlement trough, taken as, $2.5i$, i.e. where $S_v/S_{max} = 0.044$. In any calculation of building strain, the building span length is required and is defined as the length of building in a hogging or sagging zone (i.e. L_h or L_s as shown on Figure 5) and limited by a point of inflexion or extent of settlement trough as described.

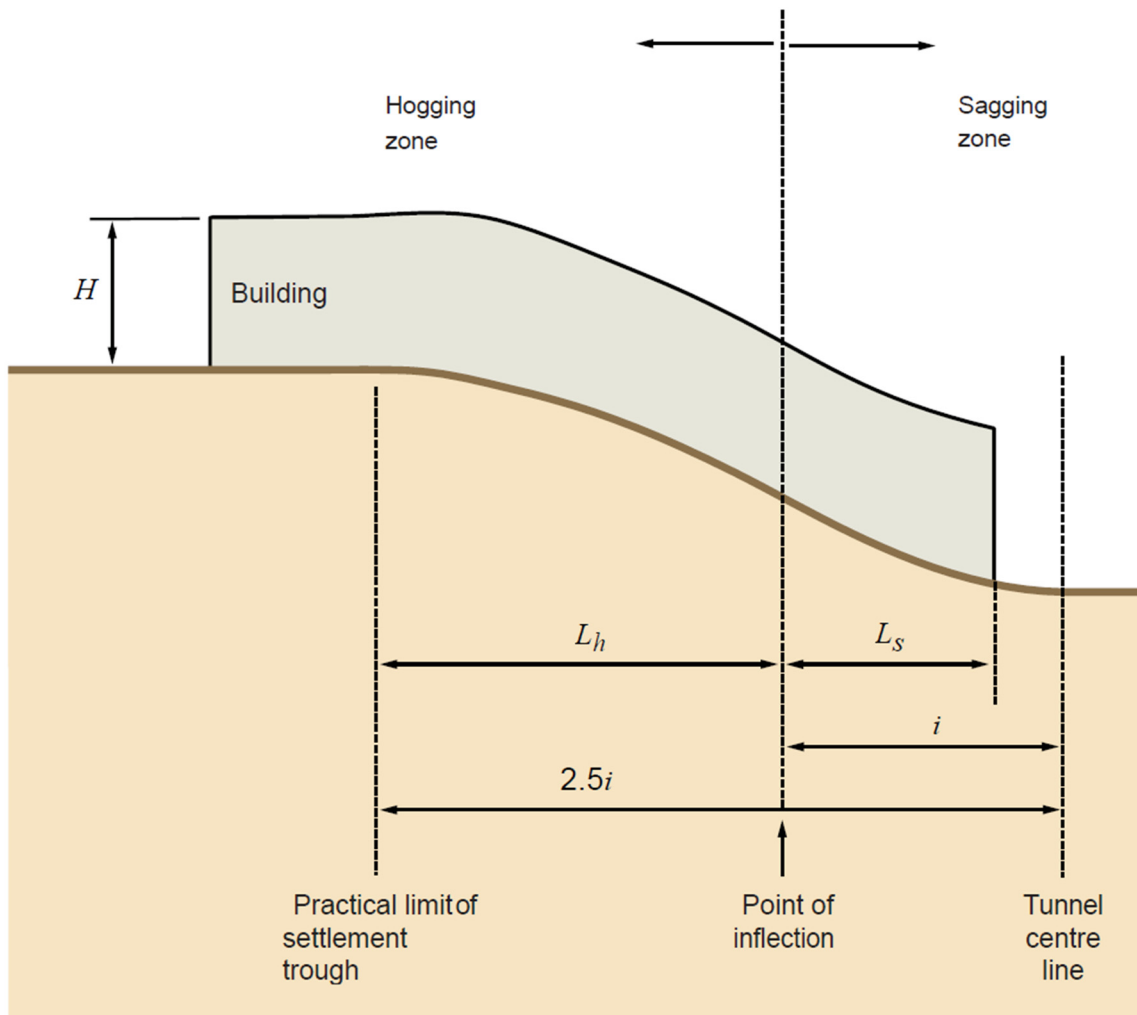


Figure 5: General case of a building affected by a tunnelling settlement trough

3.2 Strains due to ground settlement

Ground movements will usually generate tensile strains in building which can lead to cracking and general damage. The problem of settlement damage to buildings was considered at length by Burland and Wroth (1974). They treated a building as an idealised beam with span L and height H deforming under a central point load to give a maximum deflection Δ . They argued that, for the portion of the building in the hogging mode, the restraining effect of the foundations would, in effect, lower the neutral axis which could therefore be taken to coincide with the lower extreme fibre of the 'beam'. For the portion of the building in the sagging mode, however, it is reasonable to assume that the neutral axis remains in the middle of the 'beam'. Burland and Wroth showed that these selections of the positions of the neutral axis are consistent with observations of building performance. Expressions were derived relating the ratio Δ/L for the beam to the maximum relative bending strain (ϵ_b) and diagonal strain (ϵ_d). The strains in a building with a maximum relative settlement Δ can also be determined from these expressions which were presented in a generalised form by Burland et al (1977) as:

$$\frac{\Delta}{L} = \left\{ \frac{L}{12t} + \frac{3I}{2tLH} \frac{E}{G} \right\} \epsilon_b$$

and

$$\frac{\Delta}{L} = \left\{ 1 + \frac{HL^2}{18I} \frac{G}{E} \right\} \epsilon_d$$

where

- H is the height of the building,
- L is the length of the building (but limited by any point of inflexion or extent of settlement trough as discussed above,
- E and G are respectively the Young's modulus and shear modulus of the building (assumed to be acting as a beam),
- I is the second moment of area of the equivalent beam (i.e. $H^3/12$ in the sagging zone and $H^3/3$ in the hogging zone), and
- t is the furthest distance from the neutral axis to the edge of the beam (i.e. $H/2$ in the sagging zone and H in the hogging zone).

The maximum bending strain ϵ_b and diagonal strain ϵ_d are likely to develop at the centre and quarter span points respectively. Although masonry is not an isotropic material, the ratio E/G is often taken as 2.6, which is consistent with an isotropic Poisson's ratio of 0.3, and this value is recommended.

Figure 5 shows a general case of a building affected by a tunnel settlement trough. It is assumed that the building follows the ground settlement trough at the foundation level. The point of inflexion of the settlement trough (defined by i for the case of a single tunnel) divides the building into two zones. In the hogging zone ($y > i$), where the neutral axis is at the bottom, all strains due to bending will be tensile.

In the sagging zone, where the neutral axis is at the centre of the building, bending will cause both compressive and tensile strains. Within each zone, the maximum ratio Δ/L can be determined, i.e. Δ_h/L_h in the hogging zone and Δ_s/L_s in the sagging zone, as shown on Figure 6. For a given ratio Δ/L , the hogging mode is likely to be more damaging than the sagging mode. This procedure essentially allows the building to be treated separately either side of the point of inflexion which is considered a reasonable approach. The maximum values of Δ_h or Δ_s are unlikely to occur at the centre of their respective span and in general it will be simplest to search for these numerically. It should be noted that this approach differs slightly from that suggested by Boscardin and Cording (1989) in which Δ/L was related to an angular distortion.

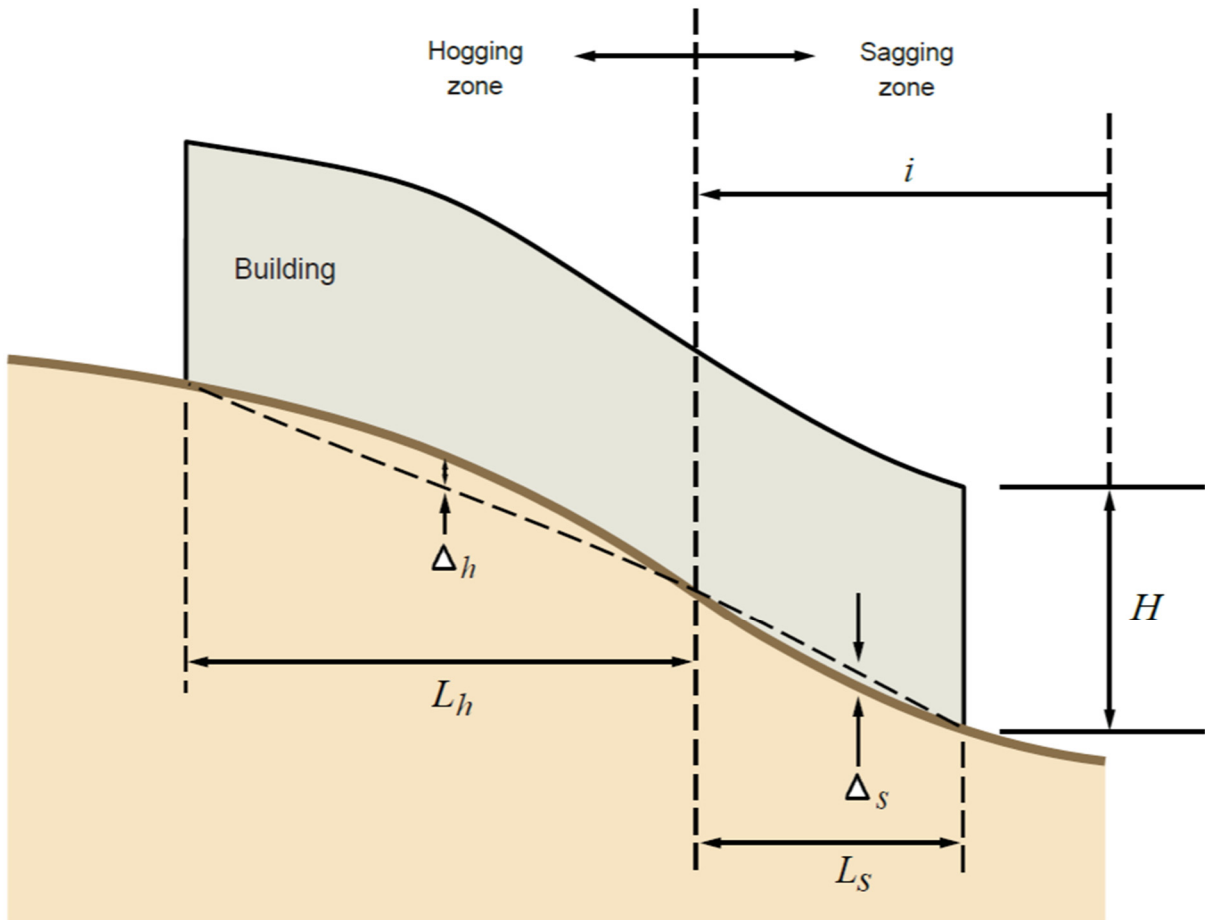


Figure 6: Determination of maximum relative settlement ratio Δ/L

In cases where the building span being considered has dimensions such that $L > H$, an additional ratio Δ_{sub}/L_{sub} should also be determined by considering smaller sub-spans of length $L_{sub} = H$ within the overall span and the associated Δ_{sub} calculated using the procedure outlined above. For a particular building span, the maximum ratio of Δ/L determined using either the full building span length or L_{sub} should then be used in Equations 13 and 14.

3.3 Superposition of horizontal ground strain

The horizontal ground strains due to bored tunnel construction will also contribute to building damage. The horizontal strains can be added directly to the bending strains giving:

$$\epsilon_{bt} = \epsilon_h + \epsilon_b$$

where ϵ_{bt} is the building strain.

In assessing building damage, the maximum tensile strain is required, and this will generally be in the hogging zone where both ϵ_b and ϵ_h are tensile.

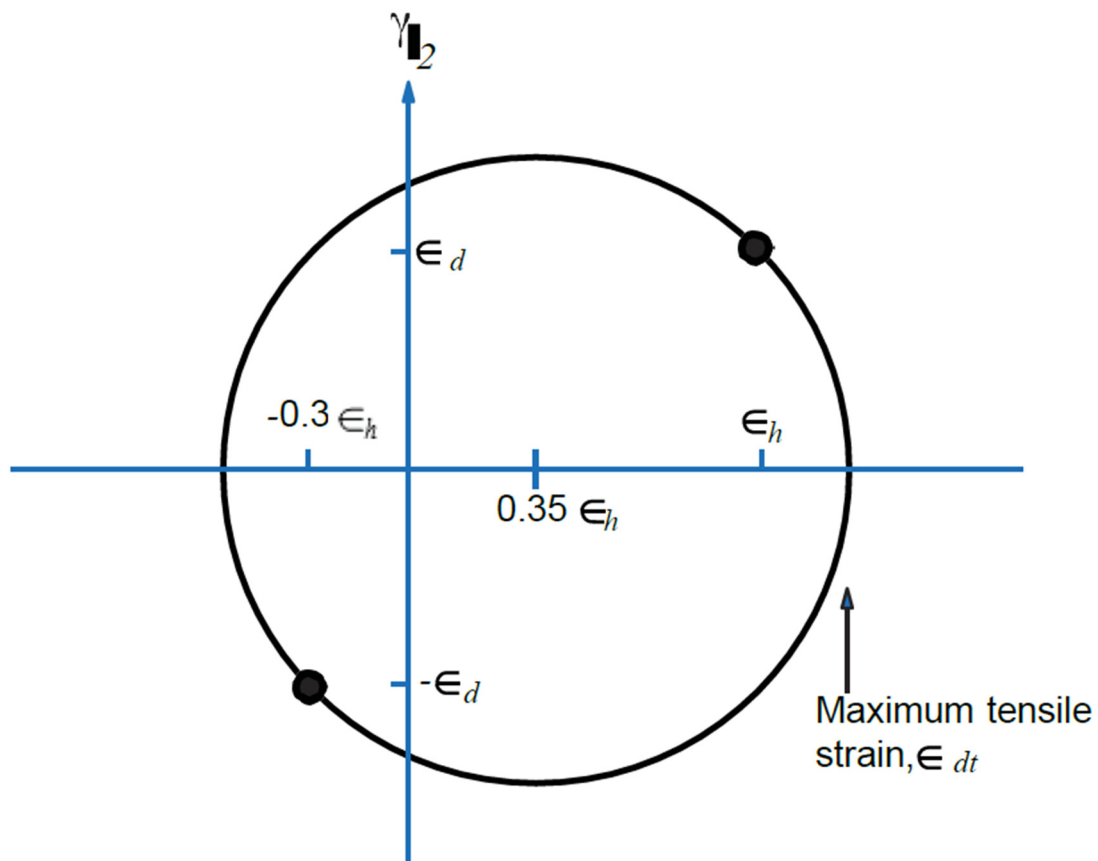


Figure 7: Mohr's circle of strain used to determine ϵ_{dt}

Diagonal (shear) strains and horizontal strains can be summoned by making use of Mohr's circle of strain as shown on Figure 7. If a tensile horizontal strain, ϵ_h , is induced in the building, then in the vertical direction a compressive strain of $-0.3\epsilon_h$ will result (assuming a Poisson's ratio of 0.3). Two points on the Mohr's circle are then (ϵ_h, ϵ_d) and $(-0.3\epsilon_h, -\epsilon_d)$ and the circle can be constructed as shown. The maximum tensile strain due to diagonal distortion, ϵ_{dt} is then given by:

$$\epsilon_{dt} = 0.35 \epsilon_h + [(0.65 \epsilon_h)^2 + \epsilon_d^2]^{0.5}$$

A question arises when determining the appropriate value of ϵ_h . The recommended approach is to use Equations 5 and 6 to calculate the horizontal movement at either end of a building span under consideration and the difference between these divided

by the span length then gives an average horizontal strain. If a sub-span gives the maximum Δ/L ratio, the average horizontal strain should be calculated for the particular sub-span used. Calculation of local horizontal strain using Equation 8 is considered unduly conservative and is not recommended.

4 Assessment of Damage

4.1 Damage to buildings by settlement will be classified into various categories of risk as given in Burland et al (1977) and in the Building Research Establishment Digest 251: negligible, very slight, slight, moderate, severe and very severe. These categories, together with typical repairs that might be required for masonry buildings, are described in Table 1, Boscardin and Cording (1989) showed that these categories of damage are related to the magnitude of the maximum tensile strain induced in the structure, as shown in Table 1.

4.2 References

Boscardin, M.D. and Cording, E.J. (1989). Building response to excavation induced settlement. *Journal of Geotechnical Engineering, ASCE*, Vol. 115, No 1, pp 1-21.

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Burland, J.B., Broms, B.B. and de Mello, V.F.B. (1977). Behaviour of foundations and structures. State-of-the-art report, Session 2, Proc. 9th Int. Conf. on Soil Mechanics and Foundation Engineering, Tokyo. Vol. 3, pp 495-546.

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O'Reilly, M.P. and New, B.M. (1982). Settlements above tunnels in the United Kingdom – their magnitude and prediction. *Tunnelling '82*. Ed Jones, M.J. pp 173-181. London, IMM.

New, B.M. and Bowers, K.H. Ground movement model validation at the HEATHROW EXPRESS TRIAL TUNNEL – *Tunnelling '94*. pp 301-329. IMM. London.

Degree of	Description of typical damage (ease of repair is in bold text)	Approximate crack width	Limiting tensile strain
0 Negligible	Hairline cracks of less than about 0.1mm are classed as negligible.	< 0.1	0.0-0.05
1 Very slight	Fine cracks which can easily be treated during normal decoration. Perhaps isolated slight fracture in building. Cracks in external brickwork visible on close inspection.	1	0.05-0.075
2 Slight	Cracks easily filled. Re-decoration probably required. Several slight fractures showing inside building. Cracks are visible externally and some repointing may be required externally to ensure weathertightness. Doors and windows may stick slightly.	5	0.075-0.15
3 Moderate	The cracks require some opening up and can be patched by a mason. Recurrent cracks can be masked by suitable linings. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired.	5 to 15 or a number of cracks > 3	0.15-0.3
4 Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing in beams. Service pipes disrupted.	15 to 25 but also depends on number of cracks	> 0.3
5 Very Severe	This requires a major repair job involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.	usually > 25 but depends on number of cracks	
* In assessing the degree of damage, account must be taken of its location in the building or structure. ** Crack width is only one aspect of damage and should not be used on its own as a direct measure of it.			

Table 1: Classification of visible damage to walls with particular reference to ease of repair of plaster and brickwork or masonry (after Burland, Broms and de Mello, 1977; Boscardin and Cording, 1989)

5 Summary of Calculation Procedure and Building Assessment

- 5.1 For each tunnel likely to affect a building, determine the depth Z from the cross section. Choose relevant values for V_l and K and determine V_s (Equation 3) and i (Equation 4) for each tunnel. Also calculate S_{\max} (Equation 2) for each tunnel.
- 5.2 Determine points of inflexion of the settlement profile beneath the building. This may involve the calculation of curvature where there are multiple tunnels (Equation 12). Hence define relevant building span lengths which will be limited by the extent of the building, the practical limit of the settlement trough and points of inflexion as appropriate.
- 5.3 Calculate values of S_v (Equation 5) and S_h (Equation 6) at the ends of the building span lengths.
- 5.4 Use the change in S_h over the span length L to determine the average horizontal strain, ϵ_h .
- 5.5 For each building span, calculate the average horizontal strain and the maximum ratio. NB an additional search for maximum Δ/L ratio is to be undertaken for sub-spans when L exceeds H , and if this value of Δ/L is used, the average horizontal strain should be recalculated for the relevant sub-span.
- 5.6 Calculate values for ϵ_b (Equation 13) and ϵ_d (Equation 14) and combine these to determine the maximum combined strains ϵ_{bt} (Equation 15) and ϵ_{dt} (Equation 16). Classify the building damage based on the maximum tensile strain according to Table 1.

Appendix B

Noise and Vibration Assessment Summary

Crossrail 2

Noise and Vibration Assessment and Mitigation

Report No MTEW/1i3
Resiliently Supported Track
Tunnel Vibration Predictions

August 2016

<h1>Crossrail 2</h1>						
Noise and Vibration Assessment and Mitigation						
Report No MTEW/1 Tunnel Vibration Predictions						
Issue and Revised Record						
Issue	Date	Originator	Checked	Approved	Description	Status
2	09/02/2016	RMTT	FLT	RMTT	Report	2 nd Issue
3	08/08/2016	RMTT	FLT	RMTT	Report	3 rd Issue

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1 Introduction

- 1.1 This report provides predictions of the vibrations of the wall of the tunnels in the Crossrail 2 central section, for use in the assessment of groundborne noise in adjacent buildings.

2 Description of the Model

- 2.1 The prediction model used for these predictions employs an algorithm for the solution of the wave equation for the propagation of waves in bars, plates and solids, using finite difference methods. The model computes vibration of each element as a function of time, which is then subjected to Discrete Fourier Transform using a standard Fast Fourier Transform algorithm. The bandwidth of the prediction results covers the 1/3 octave bands centred on 10Hz to 250Hz.
- 2.2 The model consists of a section of tunnel the length of one complete train consisting of nine vehicles, connected end-to-end to create an infinitely long tunnel and train. In view of the fact that the length of a Crossrail 2 train is many times the tunnel diameter, the modelling of an infinitely long train is valid. The tunnel is modelled as a tube surrounded by soil. Each rail is modelled as a beam supported on periodic resilient supports. The train is represented by the unsprung masses of the wheels and associated equipment, the sprung bogie masses, the secondary suspension and the car body.

3 Assumptions

3.1 Track

The track was modelled as the system installed on Crossrail 1, Sateba S312S3.

3.2 Vehicles

The vehicles were modelled as Bombardier Class 345 using data as at December 2014.

3.3 Tunnel Design

The tunnel assumption was a 6.4m inside diameter tunnel with 400mm thick concrete linings.

3.4 Rail Roughness

A roughness spectrum of 30dB re 1 micron in the 1/3 octave band centred on a wavelength of 2m, sloping at a rate of -15dB per decade to 0dB in the 1/3 octave band centred on 0.02m, This spectrum was used to represent the combined effects of wheel and rail roughness.

3.5 Soil

The soil characteristics used were those of London Clay. The compression wave speed assumed was $c_s=1610$ m/s and the loss factor $\eta =0.1$.

4 Prediction Results

- 4.1 The results are presented in tabular form in Table 1 and Table 2 for two train speeds of 80km/h and 100km/h respectively, in terms of 1/3 octave spectra of radial tunnel wall velocity in decibels re 1 nanometre per second, for 40 positions around the tunnel circumference. The same data are also plotted in Figure 1, Figure 2, Figure 3 and Figure 4.

5 Application of the Results

- 5.1 The results may be used for estimating the likely level of groundborne noise inside buildings above the tunnel alignment. For this purpose, it is necessary to take account of the effect of vibration propagation through the soil, of coupling loss factor between the soil and the building, and the dynamic response of the building. After applying corrections for these effects, the results in terms of the root-mean-square (rms) velocity in 1/3 octave bands can be used to estimate the sound pressure level inside a typical room. In many cases, the relationship between room sound pressure level and 'rms' velocity of the room surfaces is approximately equivalent to $L_p = L_v - 27dB$, where L_p is the 1/3 octave band sound pressure level: L_v is the 'rms' vibration velocity in dB re 1 nanometre per second¹.
- 5.2 Propagation through the soil is a very complex phenomenon, since the vibration is propagated in three way – as shear, compression and surface waves, and as shown by the results given in this report, the source strength varies around the tunnel circumference. A worst-case approach would be to take the highest levels in the tunnel wall 'visible' to the receiving structure, and use a distance function as follows:

$$L_r = L_t - 4.34 \frac{\omega \eta r}{c_s} - 10 \log_{10} \left[\frac{r_0 + r}{r_0} \right]$$

Where L_t is the tunnel wall radial velocity for a tunnel of radius r_0 and L_r is the soil velocity at distance r , both in dB re 1 nanometre/second, c_s , is the phase speed of compression waves in soil with loss factor η and ω is the angular frequency of each 1/3 octave band in radians per second². The coupling loss factor and building response generally have opposite sign and as a first order approximation they may be assumed to cancel. In the case of piled foundations, if r is taken to be the shortest distance to any part of the nearest pile, a worst-case estimate will be obtained. Any distance units may be used, provided they are consistent throughout.

- 5.3 The overall 1/3 octave spectrum may be converted to dB(A) by decibel addition of the band levels after applying the value of the 'A-weighting' curve of each band centre frequency.

¹ Thornely-Taylor R. The relationship between floor vibration from an underground source and the airborne sound pressure level in the room. International Journal of Rail Transportation 4(4), 2016, pp.247-255

² ISO/TS 14837-32:2015 Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 32: Measurement of dynamic properties of the ground

5.4 To obtain a more precise prediction of groundborne noise levels in buildings, it is necessary to use numerical modelling methods based on finite-difference or finite-element techniques.

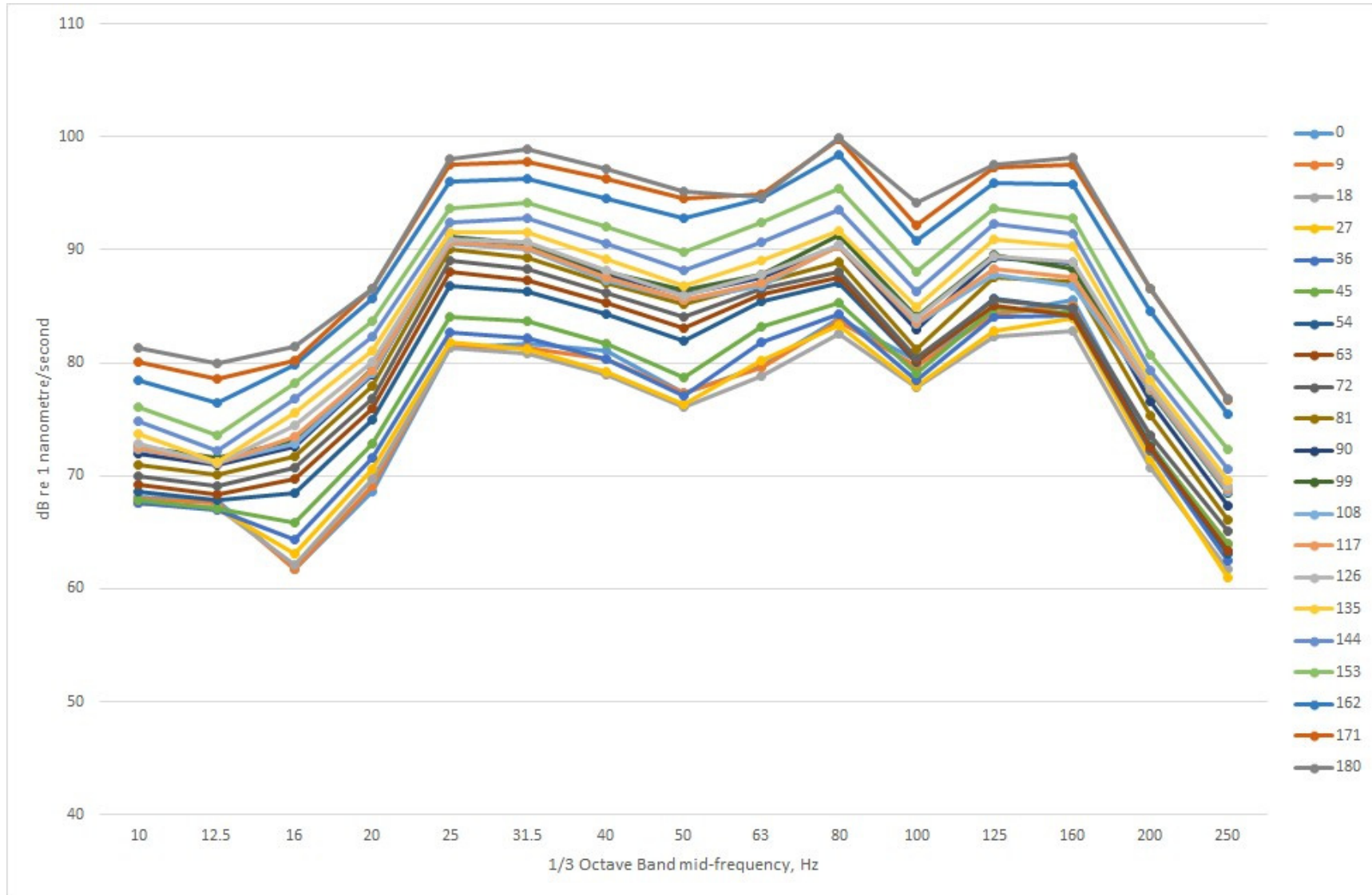


Figure 1: Distribution of vibration levels around tunnel circumference (0 degree - crown) 80km/h

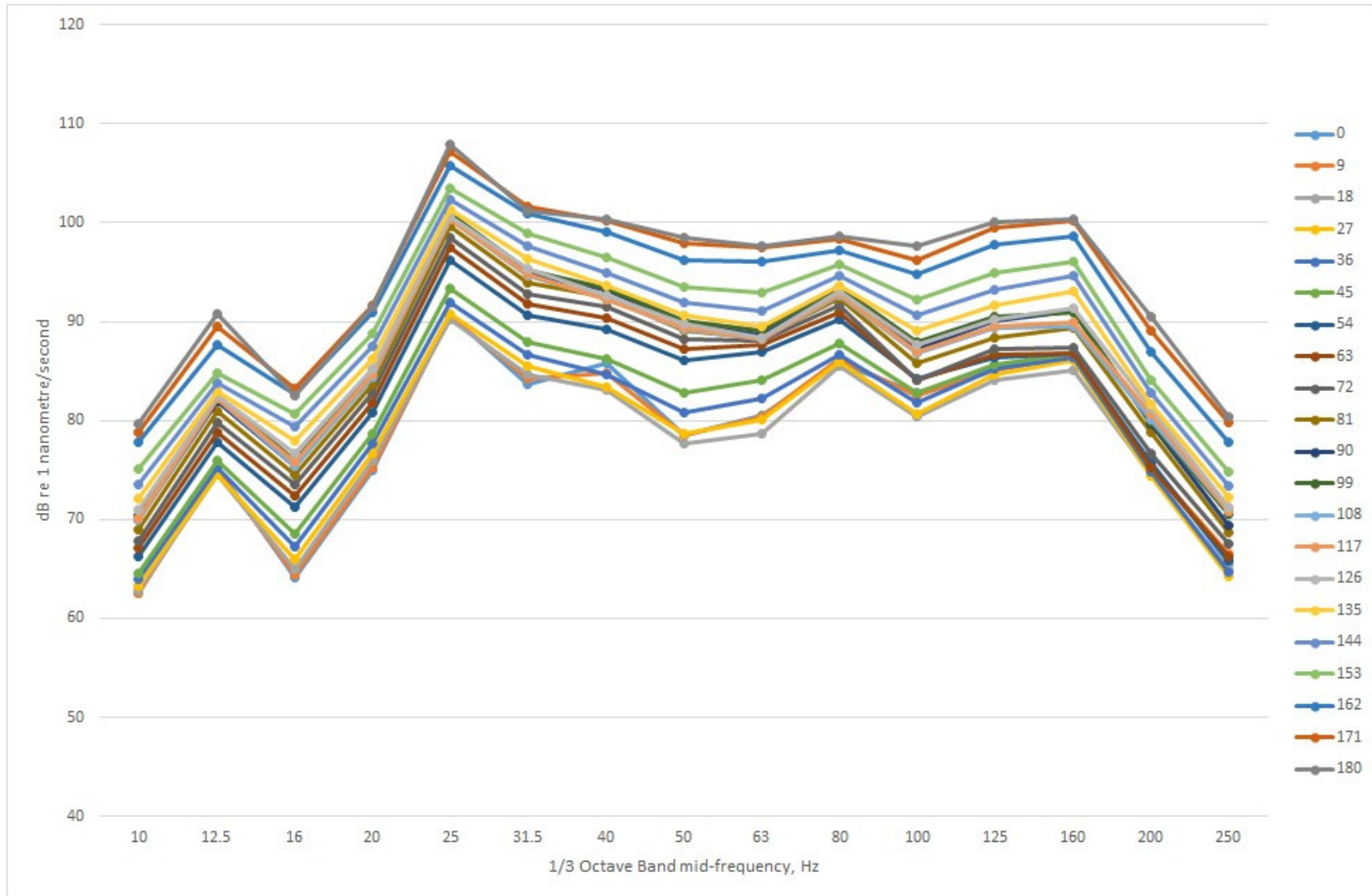


Figure 2: Distribution of vibration levels around tunnel circumference (0 degrees - crown) 100 km/h dB re 1 nm/s

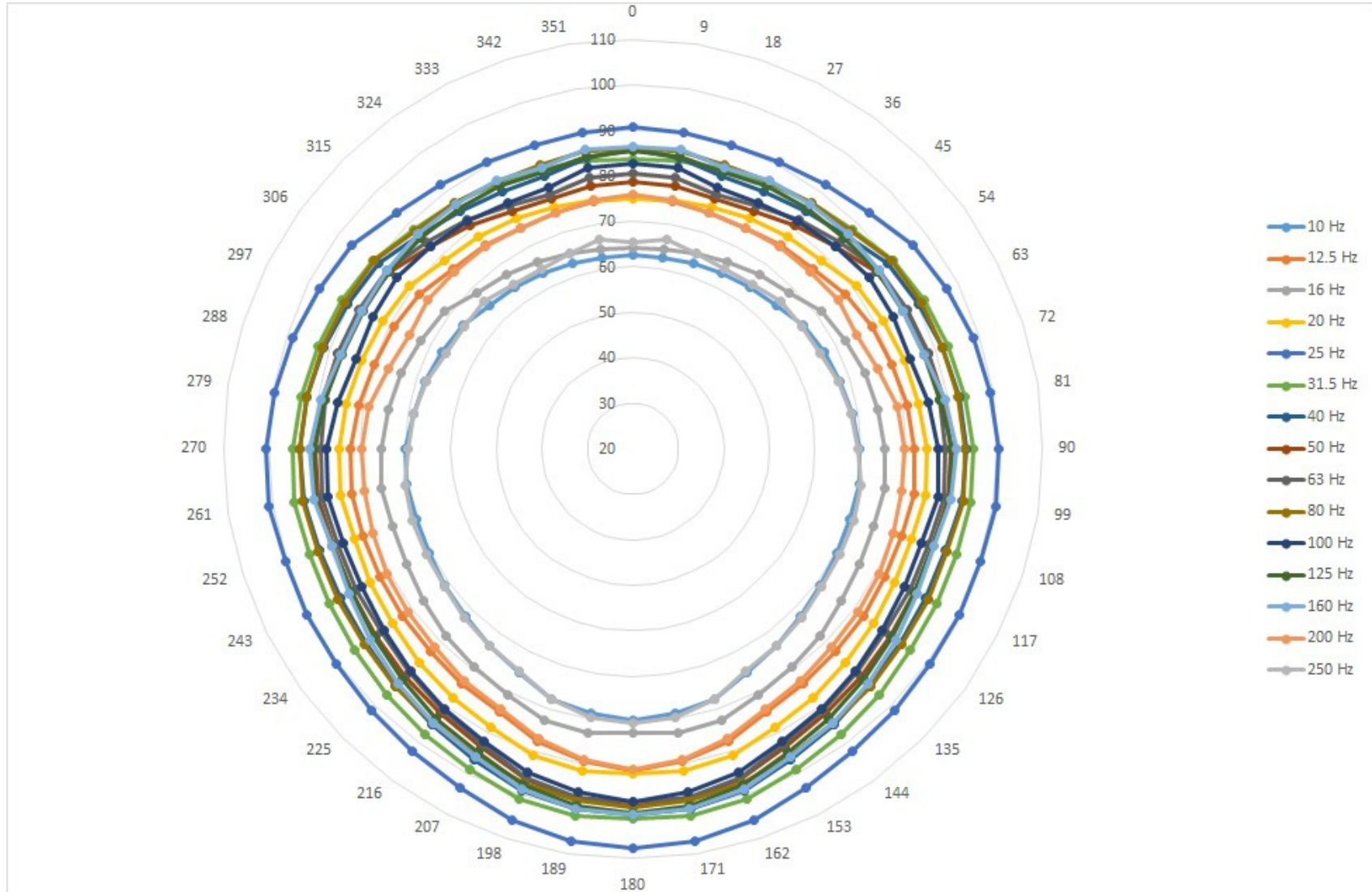


Figure 3: Distribution of vibration levels around tunnel circumference - 80 km/h dB re 1 nm/s

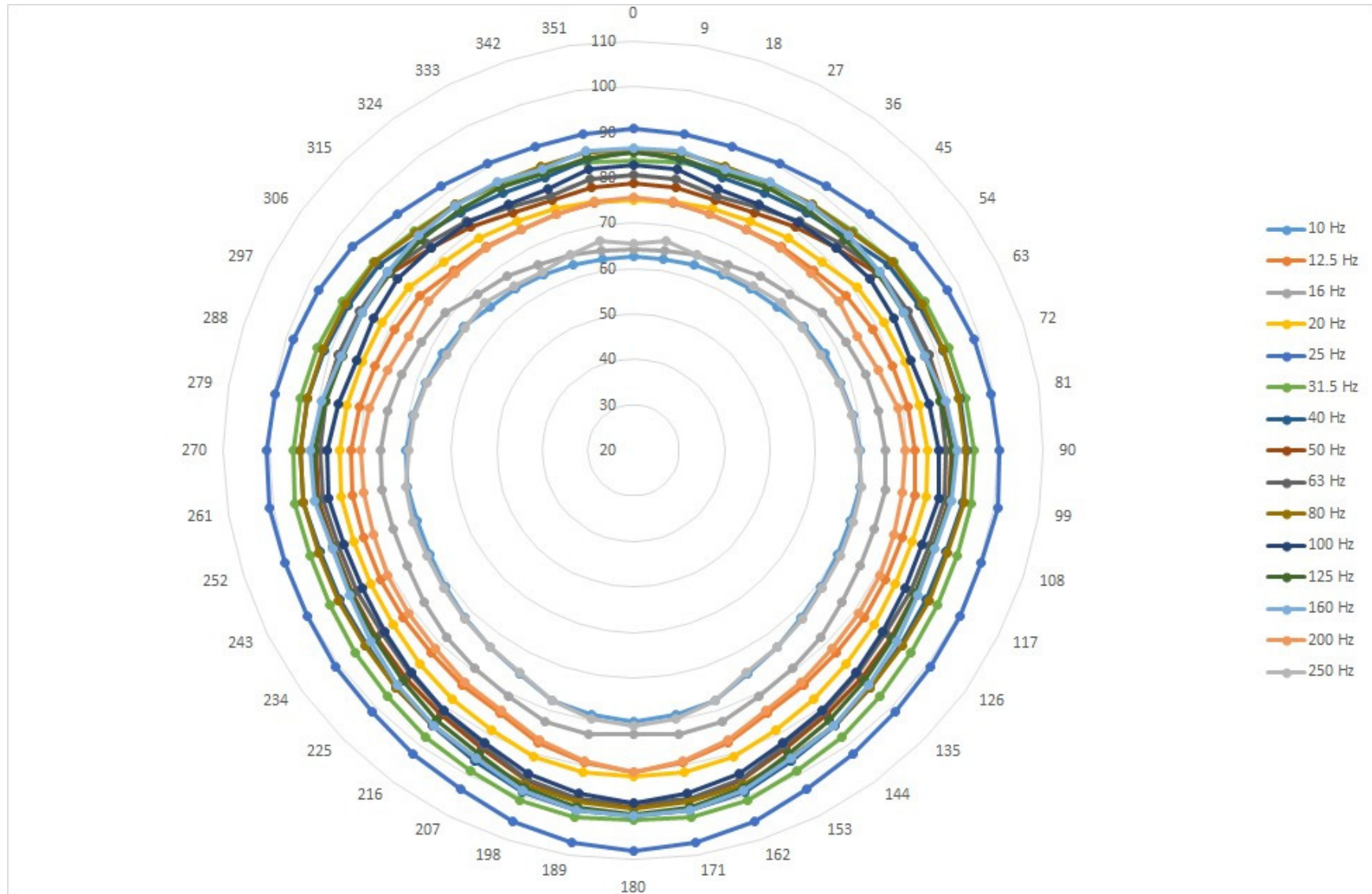


Figure 4: Distribution of vibration levels around tunnel circumference - 100 km/h dB re 1 nm/s