Lower Thames Crossing

6.3 Environmental Statement Appendices
Appendix 12.6 – Assessment of Ground-borne Noise and Vibration at land-based receptors

APFP Regulation 5(2)(a)

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Lower Thames Crossing

Appendix 12.6 – Assessment of Ground-borne Noise and Vibration at land-based receptors

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1 Introduction

1.1.1 Rupert Taylor Ltd was instructed by Arcadis to carry out a study of the likely level of ground-borne noise and vibration from the excavation of tunnels for the proposed A122 Lower Thames Crossing ('the Project'), as well as tunnels of smaller diameter for advanced grouting works and utility diversions as detailed in Annex B, using tunnel boring machines (TBM). Annex B includes assumptions on which the assessment was based and are subject to change at detailed design or following further investigation and is permitted if it gives rise to no new or different environmental effects.

1.1.2 The study has been carried out in two parts. The first part concentrated on the effects of vibration and underwater sound on aquatic species in the River Thames (Appendix 9.1, Application Document 6.3). This second part is devoted specifically to land-based sensitive receptors and is presented herein.

1.1.3 North of the River Thames, the distances to receptors are so great that land-based receptors here would not experience any measurable noise or vibration from the TBMs. South of the river, there are a small number of receptors which have been considered in this study. Separate consideration has been given to ground-borne noise and vibration from the main tunnel drive, and from the advanced grouting works and utilities tunnel drives.

1.1.4 Models were created to study the propagation of vibration from the tunnel face, with the TBM operating in the soils which are likely to occur along the alignment. The output of the modelling is an indication of likely ground-borne vibration and associated ground-borne noise.

2 Background

2.1.1 The factors which influence the generation and propagation of ground-borne vibration and noise from TBMs are primarily the amount of energy required to cut the soil or rock and the propagation characteristics of the soil. Rotational speed, cutter head type and face pressure have a much smaller effect. The energy requirement is a function of the tunnel diameter and the operating characteristics of the machine. The proposed Project tunnels are likely to be approximately 16.5m diameter. For context the diameter of the Jubilee Line Extension TBM face was 4.9m, Dublin Port Tunnel was 11.8m, Crossrail was 7.1m, High Speed 1 London tunnels were 8.15m and the Silvertown Tunnel is designed to be 12.5m diameter.

2.1.2 Soil type is a major influence, with London Clay being soft enough for the main noise from the TBM to be its machinery. At the other extreme, excavating through rock generates a large amount of noise and vibration due to the cutting effect itself. Previous tunnels in the UK and Ireland were in a variety of lithologies. Dublin is carboniferous limestone below glacial till. The tunnels in London are in London Clay, Gravel, Lambeth Beds, Chalk and Thanet sands. The Silvertown tunnel will be bored through clay, gravel and sand. The Project tunnels will be driven through weak chalk under the Thames, below layers of river terrace deposits and alluvium, including some clay and gravel.

2.1.3 Whilst the main tunnel TBMs are likely to be slurry machines, from a vibration point of view there is little difference between slurry and earth-pressure-balance machines for the same soil conditions.

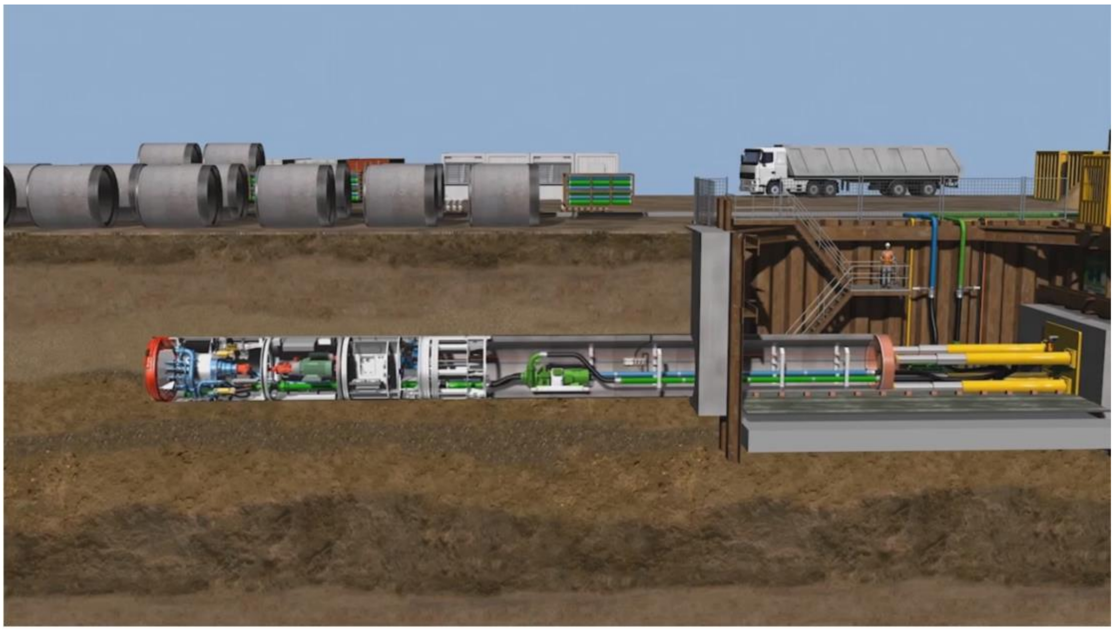
3 Prediction of vibration and noise from TBMs

3.1.1 The prediction of vibration and ground-borne noise from TBMs has to begin with measured field data, used to calibrate the output of a model for predicting the spatial spread of the vibration (which in turn may also cause ground-borne noise). In stiff or hard soils the source is concentrated at the cutter face. In soft soil, ground-borne noise may be radiated from the entire length of the TBM, which can reach lengths of 100m or so (Plate 3.1).

Plate 3.1 Cutaway view of a large diameter tunnel boring machine (Herrenknecht)

3.1.2 In the case of micro-TBMs, there is a smaller-sized TBM coupled with a jacking system in which pipe segments are jacked behind the TBM both from hydraulic jacks in the launch pit and intermediate jacks along the length of the tunnel. An example cutaway illustration is shown in Plate 3.2.

Plate 3.2 Cutaway view of a micro tunnel boring machine and pipejacking system (Herrenknecht AVN)



4 Numerical modelling

4.1.1 The predictions of vibration and ground-borne noise were carried out using the Rupert Taylor Finite Difference Time Domain model, FINDWAVE®.

4.1.2 The model used for this study predicts, in the time domain, the three-dimensional vibration velocity of the tunnel face and surrounding lithology. The time-domain results are transformed into the frequency domain to give 1/3 octave frequency spectra, and overall sound levels in dB(A) and vibration units.

4.1.3 The model has been calibrated by using the model to predict vibration from the Crossrail TBM, and backfitting the results from field measurements obtained during the tunnel drive. Differences in the hardness of the lithology are taken into account through the cell properties assigned to the material at the tunnel face.

4.1.4 There are some measured vibration data relating to the Herrenknecht AVN micro-TBM in the literature (Rallu *et al*., 2022) and the output of the present modelling study favourably compares with measurements reported therein.

4.1.5 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 Annex A. The excitation is provided from a random array of impulses applied to the tunnel face. The model predicts, in the time domain, the dynamic behaviour the medium surrounding the tunnel face.

4.1.6 The model has a cell size of 200mm in the lateral and vertical directions, and 200mm in the longitudinal direction (along the tunnel). A time step of 1/131072 seconds was used. The model was run for a time period of 1 second. Output from the model consists of time series of the velocity of transverse and longitudinal sections through the model, which are subjected to frequency transformation and expressed as 1/3 octave band spectra.

5 Modelling assumptions used

5.1.1 This geotechnical data assumed in the modelling was taken from Chapter 10 Geology and Soils (Application Document 6.1) based upon the Phase 1 and 2 ground investigation surveys.

5.1.2 The tunnel behind the main TBMs and the advanced grouting tunnel TBM was assumed to be lined with concrete. The micro-TBM tunnels are assumed to be lined with prefabricated pipe segments. It has been assumed that the normal practice in the driving of twin tunnels will be followed in which the two TBM faces do not occur side by side and that one will lead the other by sufficient distance to avoid effects in combination from the two tunnels. The effect if two TBMs were to operate close together, is discussed below.

5.1.3 Examples of generic outputs from a typical TBM model are shown in Plate 5.1 and Plate 5.2

Plate 5.1 Generic long section through a typical TBM model

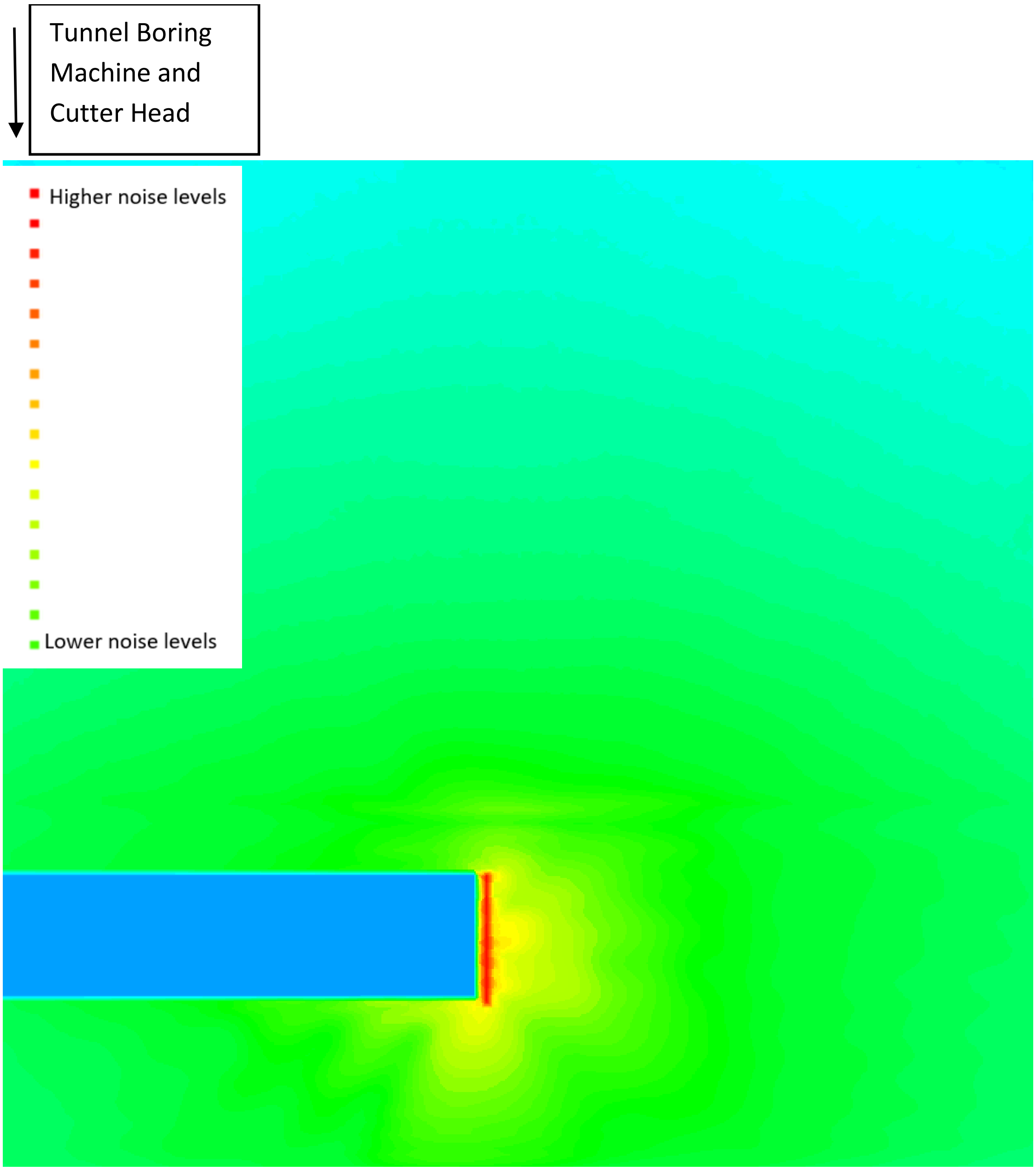
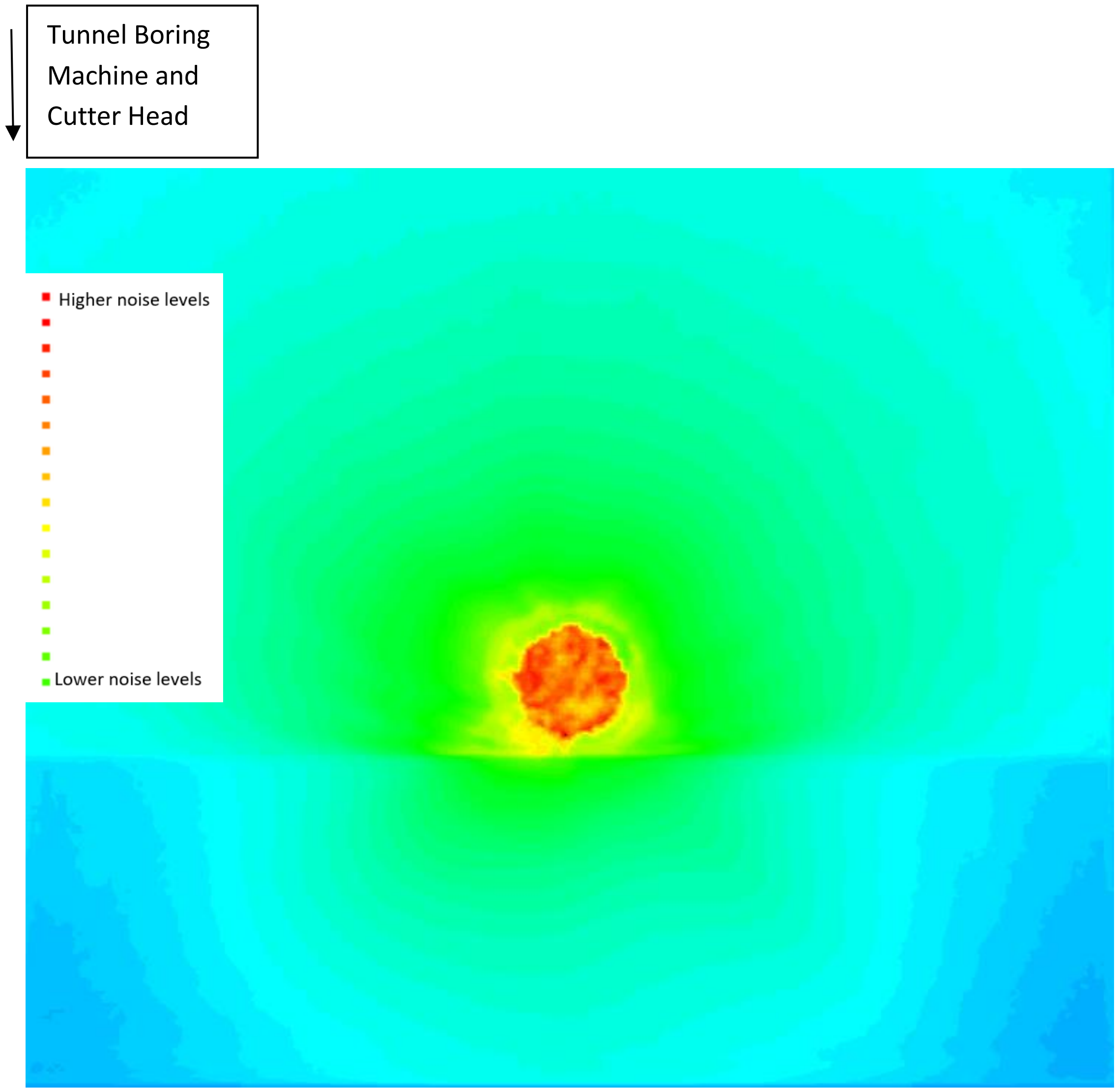


Plate 5.2 Generic cross section through a typical TBM model



6 Assessment

6.1 Significance Criteria

6.1.1 The essential feature of vibration and ground-borne noise from a TBM is that it is transitory, and is seldom perceptible for longer than a few days. However, it is common practice to operate a TBM continuously, day and night.

6.1.2 There are no separately established criteria for ground-borne noise and vibration from tunnel boring. A preliminary assessment can be made using criteria for ground-borne noise and vibration for permanent sources such as the operation of underground railways. This approach has been developed based on professional judgement and expert experience, and was first adopted in the Environmental Assessment of the Silvertown Tunnel project leading to the grant of its Development Consent Order.

6.1.3 On this basis, as far as noise policy thresholds are concerned, Table 6.1 shows the Significant Observed Adverse Effect Level (SOAEL) and the Lowest Observed Adverse Effect Level (LOAEL) for residential receptors.

Table 6.1 Assessment thresholds for ground-borne noise and vibration on people in residential receptors

Ground-borne noise	Lowest Observed Effect Level (Negligible)	L_{pASmax} dB	25
	Lowest Observed Adverse Effect Level	L_{pASmax} dB	35
	Significant Observed Adverse Effect Level	L_{pASmax} dB	45
Vibration	Lowest Observed Effect Level (Negligible)	VDV_{day} m/s$^{-1.75}$	0.1
		VDV_{night} m/s$^{-1.75}$	0.05
	Lowest Observed Adverse Effect Level	VDV_{day} m/s$^{-1.75}$	0.2
		VDV_{night} m/s$^{-1.75}$	0.1
	Significant Observed Adverse Effect Level	VDV_{day} m/s$^{-1.75}$	0.8
		VDV_{night} m/s$^{-1.75}$	0.4

6.1.4 With regard to non-residential receptors Table 6.2 shows thresholds for vibration effects on people; and Table 6.3 shows thresholds for vibration effects on structures. Table 6.4 shows ground-borne noise thresholds for non-residential receptors. As mentioned above, in the absence of separately established criteria for ground-borne noise and vibration from tunnel boring, this approach has been developed using professional judgement and was adopted in the Environmental Assessment of the Silvertown Tunnel project leading to the grant of its Development Consent Order.

Table 6.2 Assessment thresholds for vibration effects on people in non-residential receptors

	$VDV_{b,day}$ [$m/s^{-1.75}$]	$VDV_{b,night}$ [$m/s^{-1.75}$]
Hotels; hospital wards; and education dormitories, hostels, assisted living, nursing homes, homeless hubs	0.2	0.1
Offices; schools; and places of worship	0.4	n/a
Workshops	0.8	n/a
Vibration-sensitive research and manufacturing (e.g. computer chip manufacture); hospitals with vibration-sensitive equipment and operations; universities with vibration-sensitive research equipment and operations	Risk assessment will be undertaken based on the information currently available for the relevant equipment and process, or where information is provided by the building owner or equipment manufacturer.	

Table 6.3 Assessment thresholds for vibration effects on structures in PPV

Category of building	Peak component particle velocity in frequency range of predominant pulse	
	4Hz to 15Hz	15Hz and above
Reinforced or framed structures. Industrial and heavy commercial buildings	50mm/s transient vibration	
Unreinforced or light framed structures. Residential or light commercial-type buildings	15mm/s at 4Hz increasing to 20mm/s at 15Hz	20mm/s at 15Hz increasing to 50mm/s at 40Hz and above

Table 6.4 Assessment thresholds for ground-borne noise in non-residential receptors

Building	Level/measure
Theatres	25dB L_{ASmax}
Large auditoria/concert halls	25dB L_{ASmax}
Studios	30dB L_{ASmax}

Building	Level/measure
Churches	35dB L_{ASmax}
Courts, lecture theatres	35dB L_{ASmax}
Small auditoria/halls	35dB L_{ASmax}
Schools colleges	40dB L_{ASmax}
Hospitals, laboratories	40dB L_{ASmax}
Libraries	40dB L_{ASmax}

6.2 Receptors considered

6.2.1 Between the North Portal and the River Thames there are no receptors at a close enough distance to receive any observable effect. Between the South Portal and the River Thames there are few potentially sensitive receptors for ground-borne noise and vibration, as is evidenced from the extract from the Ordnance Survey shown in Plate 6.1.

6.2.2 The receptors selected for assessment are identified within a spatial scope of 500m from the nearest point of the relevant tunnel, along with the Thames and Medway Canal which is assessed as a potentially sensitive structure. The buildings assessed for the main tunnel drive are shown in Table 6.5, and the buildings assessed for the advanced grouting tunnel are shown in Table 6.6.

Table 6.5 Selected buildings for assessment – main tunnel TBM

Building	Distance from centreline [m]	
	Northbound	Southbound
84 & 86 Castle Lane	118	150
Viewpoint Place	129	161
St Mary's Church	441	409

Table 6.6 Selected buildings for assessment – advanced grouting tunnel TBM

Building	Distance from tunnel launch shaft [m]
84 & 86 Castle Lane	134
Viewpoint Place	>500m
St Mary's Church	>500m

6.2.3 As Viewpoint Place and St Mary the Virgin Church are more than 500m from the tunnel launch shaft, the nearest part of the advanced grouting tunnel, they are scoped out of the assessment of the advanced grouting tunnel.

6.2.4 The canal when directly above the tunnel has a shortest slant distance to the main tunnel axis of 25.6m. In the case of the advanced grouting tunnel, taking the upper limit of deviation, the shortest distance to the tunnel axis is 7.5m.

6.2.5 With regard to the utilities tunnels, only tunnels related to Works No. G3 and G4, which are close to Thong Lane, are located such that the shortest distance to a receptor is less than 50m, a distance which, as is evident from the results presented below (Table 6.7), is an appropriate study boundary. Although 38 Thong Lane is slightly beyond 50m, the receptor has been included to confirm the conclusions of the assessment.

Table 6.7 Distance of receptors from utilities tunnels

Receptor	Distance from tunnel centreline [m]	
	Works No. G3	Works No. G4
Baylis Landscape Contractors Ltd, Hartshill Nursery Thong Lane*	13	36
37 Thong Lane	42	63
Hartshill Bungalow Thong Lane	38	70
38 Thong Lane	52	73

** To be demolished as a result of the Project, no assessment required.*

Plate 6.1 Locations of receptors assessed

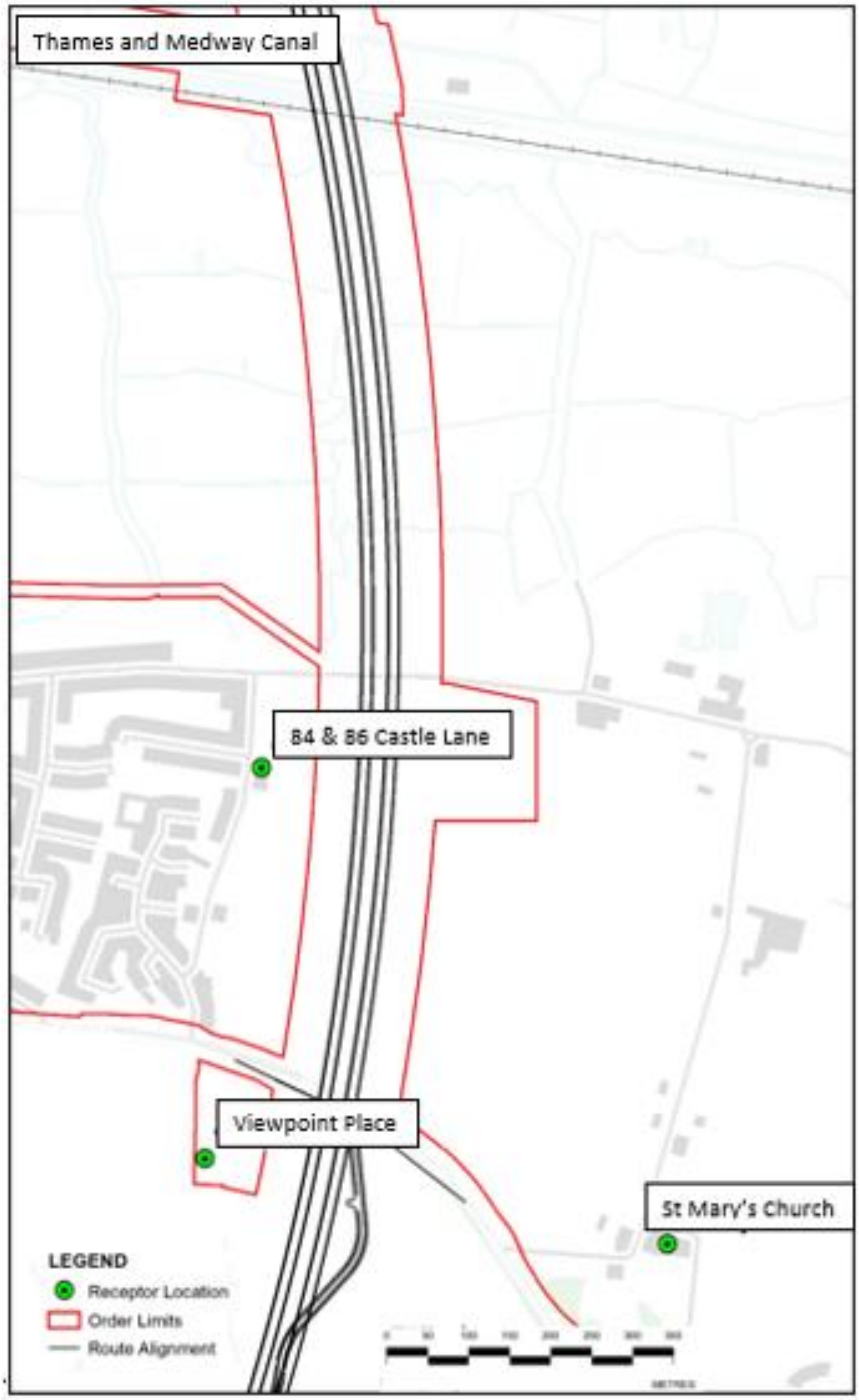


Plate 6.2 Locations of receptors assessed – micro-TBM Works No. G3

Plate 6.3 Locations of receptors assessed – micro-TBM Works No. G4

7 Results

7.1 Ground-borne noise

7.1.1 In overall terms, the predicted levels of ground-borne noise are shown in Table 7.1, Table 7.2 and Table 7.3.

Table 7.1 Predicted level of ground-borne noise from the main tunnel TBMs

Building	Ground-borne noise, L_{ASmax}	
	Northbound	Southbound
84 & 86 Castle Lane	-2dB	-10dB
Viewpoint Place	-5dB	-12dB
St Mary's Church	-60dB	-55dB

Table 7.2 Predicted level of ground-borne noise from the advanced grouting tunnel TBM

Building	Ground-borne noise, L_{ASmax}
84 & 86 Castle Lane	-8dB

7.1.2 These levels would be unmeasurable and well below the LOAEL.

Table 7.3 Predicted level of ground-borne noise from micro-TBM works

Receptor	Ground-borne noise, L_{ASmax}	
	Works No. G3	Works No. G4
Baylis Landscape Contractors Ltd, Hartshill Nursery Thong Lane	Demolished Buildings as a result of the Project, no assessment required	
37 Thong Lane	11dB	1dB
Hartshill Bungalow Thong Lane	13dB	-2.5dB
38 Thong Lane	6dB	-4dB

7.1.3 All these levels are below, or well below the LOAEL of 35 dB L_{ASmax} for residential receptors, the most sensitive criterion applicable to the receptors listed.

7.2 Vibration effects on structures

7.2.1 The predicted levels of vibration, in overall Peak Particle Velocity (PPV) terms are shown in Table 7.4, Table 7.5 and Table 7.6.

Table 7.4 Predicted level of ground-borne vibration on structures from the main tunnel TBMs

Building	Ground-borne vibration, PPV mm/s	
	Northbound	Southbound
Thames and Medway Canal	0.03	0.03
84 & 86 Castle Lane	0.003	0.001
Viewpoint Place	0.002	0.001
St Mary's Church	0.000007	0.000012

Table 7.5 Predicted level of ground-borne vibration on structures from the advanced grouting tunnel TBM

Building	Ground-borne vibration, PPV mm/s
Thames and Medway Canal	0.04
84 & 86 Castle Lane	0.002

Table 7.6 Predicted level of ground-borne vibration from micro-TBM works

Receptor	Ground-borne vibration, PPV mm/s	
	Works No. G3	Works No. G4
Baylis Landscape Contractors Ltd, Hartshill Nursery Thong Lane	Demolished Buildings as a result of the Project, no assessment required	
37 Thong Lane	0.0005	0.0002
Hartshill Bungalow Thong Lane	0.0006	0.0002
38 Thong Lane	0.0003	0.0002

7.2.2 These levels would be mostly unmeasurable and lower than the most demanding criteria for effects of vibration on structures as set out in Table 6.3.

7.3 Vibration effects on people

7.3.1 The predicted levels of vibration for the worst-case tunnel (either northbound or southbound), in overall VDV terms are shown in Table 7.7.

Table 7.7 Predicted level of ground-borne vibration on people from the main tunnel TBMs

Building	Ground-borne vibration, VDV $ms^{-1.75}$	
	$VDV_{b,day}$	$VDV_{b,night}$
84 & 86 Castle Lane	0.001	0.001
Viewpoint Place	0.001	0.0009

Building	Ground-borne vibration, VDV $ms^{-1.75}$	
	$VDV_{b,day}$	$VDV_{b,night}$
St Mary's Church	0.00006	0.00005

Table 7.8 Predicted level of ground-borne vibration on people from the advanced grouting tunnel TBM

Building	Ground-borne vibration, VDV $ms^{-1.75}$	
	$VDV_{b,day}$	$VDV_{b,night}$
84 & 86 Castle Lane	0.0007	0.0006

Table 7.9 Predicted level of ground-borne vibration from micro-TBM works

Receptor	Ground-borne vibration, VDV $ms^{-1.75}$			
	Works No. G3		Works No. G4	
	$VDV_{b,day}$	$VDV_{b,night}$	$VDV_{b,day}$	$VDV_{b,night}$
Baylis Landscape Contractors Ltd, Hartshill Nursery Thong Lane	Demolished Buildings as a result of the Project, no assessment required			
37 Thong Lane	0.0005	0.0004	0.0003	0.0002
Hartshill Bungalow Thong Lane	0.0006	0.0005	0.0002	0.0002
38 Thong Lane	0.0004	0.0003	0.0002	0.0002

7.3.2 Taking the worst-case assumption that these levels are continuous, these would be unmeasurable and below the LOAEL as referenced in Table 6.1.

8 Conclusions

8.1.1 A study has been carried out using numerical modelling, calibrated against measurements of previous tunnel drives, in order to predict likely levels of ground-borne vibration and ground-borne noise at receptors in the vicinity of the Project tunnel alignments, the advanced grouting tunnel and the micro-tunnels for utility diversions.

8.1.2 The predicted values are in all cases **Negligible** in the context of the assessment criteria and as such, do not give rise to a significant effect.

References

Chapter 10 Geology and Soils (Application Document 6.1)

Geological unit tables and geotechnical parameter plots

HE540039-PCI-GEN-GEN-REP-GEO-00005 Phase 1 GI final factual report

HE540039-PCI-GEN-GEN-REP-GEO-00012 Phase 1b final factual report

HE540039-PCI-GEN-GEN-REP-GEO-00012

HE540039-PCI-GEN-GEN-REP-GEO-00033 Pumping tests (South) factual report

LTC GE Geol long-section Jan20 (Main Crossing only) (updated)

LTC GE Geol long-section Feb20 (Main Crossing only) (updated)

Ph2 GI PckgA Factual Report Issue1 20Dec19 AppA-C

Phase 2 GI (Tunnels & Approaches) main boreholes proposed location plans

Phase 2 GI (Tunnels & Approaches) overwater boreholes proposed location plans

Phase 2 GI (Tunnels & Approaches) pumping test obs holes proposed location plans

Phase 2 GI North portal area prelim logs (29Jan20)

Phase 2 GI Overwater prelim logs (16Jan20)

Phase 2 GI Overwater prelim logs (Feb20)

Pilot Geophysics Report

Quaternary geology ground model (05 02 2020)

Rallu, A., Nicolas, B., Simon, C,, Denis, B. (2022) Vibrations induced by tunnel boring machine in urban areas: In situ measurements. Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2022.02.014. Accessed 05/08/2022

Vibration Monitoring Specification 2019-09-10 Rev 2

Annexes

Annex A THE *FINDWAVE*® MODEL

A.1 Introduction

A.1.1 The wave equation in differential form is as follows.

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

A.1.2 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.

A.1.3 Equation (1) can be stated in finite difference form by replacing the differential operator with the approximation

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

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

A.1.4 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).

A.1.5 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,j+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

A.1.6 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:

$$s(t) = D_l \varepsilon(t) - \int_0^{\infty} \varepsilon(t - \Delta t)\varphi(\Delta t)d(\Delta t)$$

A.1.7 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.

A.2 Boundaries

A.2.1 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.

A.2.2 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.

A.3 Input data

A.3.1 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. 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.

A.3.2 The output of the model consists of a file containing the displacement and/or velocity of one or more selected cells.

A.3.3 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 one second.

A.3.4 The resulting discrete time series can then be subjected to Discrete Fourier Transform to yield frequency spectra.

A.3.5 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.

A.4 Validation

A.4.1 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.

Annex B Assessment Assumptions

Table B.1 Main tunnel TBM assumptions

Northbound								
	Chainage	**Existing ground level**	**Ground Water Level – A***	**Ground Water Level – B****	**Tunnel Axis Level (assumed)**	**Easting**	**Northing**	**Diameter of the TBM (assumed)**
Minimum	2307	-14.34401	0	0.63099	-41.9552	567795.671	172247.344	16.5m
Maximum	6177	48.87	9.25078	3.9993	21.413	567438.482	176044.331	16.5m
Southbound								
	Chainage	**Existing ground level**	**Ground Water Level – A***	**Ground Water Level – B****	**Tunnel Axis Level (assumed)**	**Easting**	**Northing**	**Diameter of the tunnel (assumed)**
Minimum	2296	-14.0821	0	0.63131	-42.1529	567826.210	172237.212	16.5m
Maximum	6177	48.96874	9.30641	4.0673	21.1631	567468.849	176043.742	16.5m

**Ground Water Level – A: Interpreted Mean High Ground Water levels February 2014.*

Interpreted mean high EA groundwater levels February 2014. Levels based on contouring model of Environment Agency (EA) regional network of observation boreholes in Chalk, representing high groundwater level condition in winter 2013/2014. Notes: very sparse EA monitoring network around LTC; levels can be affected by groundwater abstraction wells and seasonal and climatic changes (e.g. levels have rebounded since 2014 in Ockendon area).

***Ground Water Level – B: Interpreted Mean Ground Water Levels from observed data Oct 2017 - Feb 2020.*

Interpreted mean groundwater levels from LTC GI Phases 1 and 2 monitoring data (manual dips) Oct 2017 - Feb 2020. Levels based on hydraulic connectivity between White Chalk Subgroup and River Terrace Deposits geology.

Table B.2 Advanced grouting tunnel TBM assumptions

Methodology	Description	Equipment (assumed)	Type of TBM	Diameter of the TBM (assumed)
Launch shaft	The launch shaft is situated just south of Lower Higham Road mainly within the A226 Gravesend Road Compound. The tunnel will be 5.8m below the canal and 5.8m in outer diameter. There is an upper limit of deviation, roughly 4m between ground level to the upper limit and so the tunnel diameter could potentially be slightly bigger if needed. The launch shaft is approximately 16m deep.	• 100 tonne crane (shaft building) • 600 tonne crane (TBM building) • 34 tonne excavator with telescopic grab • Piling rig with auger • Generator	Earth Pressure Balance Machine (EPBM)	5.8m outer diameter
Reception shaft	The reception shaft is proposed to be sunk in the Metropolitan police firing range, north of Thames and Medway Canal. The tunnel will be 5.8m below the canal and 5.8m in outer diameter. There is an upper limit of deviation, roughly 4m between ground level to the upper limit and so the tunnel diameter could potentially be slightly bigger if needed. The reception shaft is approximately 16m deep.	• 100 tonne crane • 34 tonne excavator with telescopic grab • Hydraulic power pack • 600 tonne crane (TBM recovery) • Generator	Earth Pressure Balance Machine (EPBM)	5.8m outer diameter

Plate B.1 Longitudinal Section of Advanced Grout Tunnel

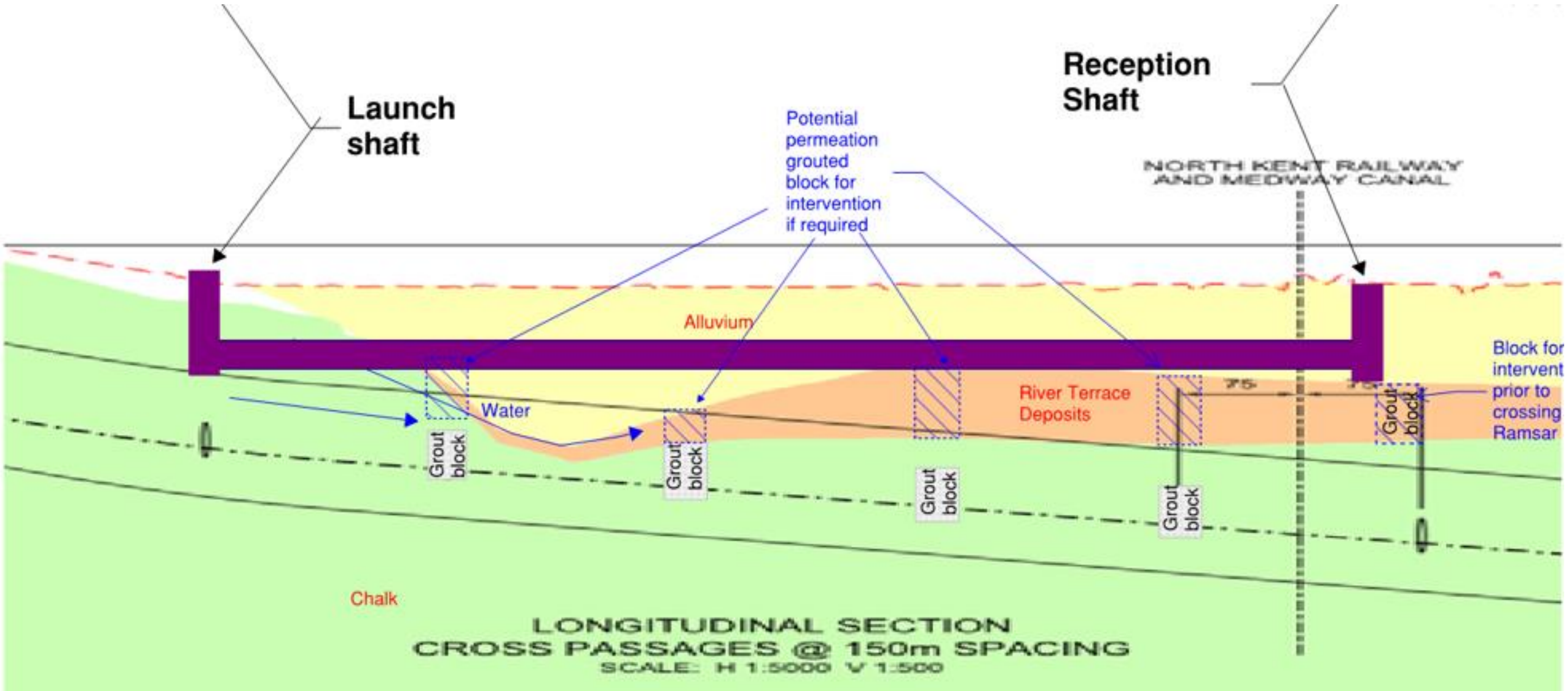


Table B.3 Micro-TBM utility diversion assumptions

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
G1b	70.010m to 71.475m (AOD)	57.24m (AOD)	566920.788	170924.085	567063.193	170830.573	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a medium pressure gas pipeline Unique works located west of Thong Construction to cross LTC: • 10m diameter launch shaft 12-15m depth • 10m diameter reception shaft 12-15m depth • Construction of tunnel via micro-TBM circa 185m length
G3 (A122)	68.699m to 69.574m (AOD)	53.892m (AOD)	567027	171091	567170	170997	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north & west of Thong Construction to cross LTC: • 9m diameter launch shaft 17-20m depth • 6m diameter reception shaft 17-20m depth • Construction of tunnel via micro-TBM circa 200m length Construction to cross Thong Lane:

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										• 16m diameter launch pit 6-8m depth • 8m diameter reception pit 6-8m depth • Installation of pipeline via auger-bore circa 45m length
G3 (Thong Lane)	68.699m to 69.341m (AOD)	65.324m (AOD)	567225	171001	567265	171008	750NB	750NB	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north & west of Thong Construction to cross LTC: • 9m diameter launch shaft 17-20m depth • 6m diameter reception shaft 17-20m depth • Construction of tunnel via micro-TBM circa 200m length Construction to cross Thong Lane: • 16m diameter launch pit 6-8m depth • 8m diameter reception pit 6-8m depth • Installation of pipeline via auger-bore circa 45m length

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
G4 (A122)	69.948m to 69.606m (AOD)	53.499m (AOD)	567030	171118	567188	171014	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north & west of Thong Construction to cross LTC: • 9m diameter launch shaft 17-20m depth • 6m diameter reception shaft 17-20m depth • Construction of tunnel via micro-TBM circa 200m length Construction to cross Thong Lane: • 16m diameter launch pit 6-8m depth • 8m diameter reception pit 6-8m depth • Installation of pipeline via auger-bore circa 45m length
G4 (Thong Lane)	68.064m to 69.180m (AOD)	64.689 (AOD)	567211	171021	567294	171046	750NB	750NB	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north & west of Thong Construction to cross LTC: • 9m diameter launch shaft 17-20m depth

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										• 6m diameter reception shaft 17-20m depth • Construction of tunnel via micro-TBM circa 200m length Construction to cross Thong Lane: • 16m diameter launch pit 6-8m depth • 8m diameter reception pit 6-8m depth • Installation of pipeline via auger-bore circa 45m length
G6 (A13)	29.49m to 27.83m (AOD)	22.5m (AOD)	566014	181556	565976	181639	1500mm	1800mm		Installation of a high pressure gas pipeline Unique works located at Green Lane, B188 High Road, Brentwood Road & A13 Construction of launch and reception pits Open cut deep dig installation circa 160m length (Green Lane) • 12m wide x 5m deep x 160m length

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										Construction of tunnel via micro-TBM circa 60m length (Brentwood Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 50m length (B188 High Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 90m length (A13) • 15m long x 6m wide x 6.2m deep launch pit, 6m long x 6m wide x 7.9m deep reception pit
G6 (A128)	27m to 25m (Google Earth interpolation)	21m (AOD) (estimated)	565386	181588	565297	181586	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located at Green Lane, B188 High Road, Brentwood Road & A13 Construction of launch and reception pits

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										Open cut deep dig installation circa 160m length (Green Lane) • 12m wide x 5m deep x 160m length Construction of tunnel via micro-TBM circa 60m length (Brentwood Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 50m length (B188 High Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 90m length (A13) • 15m long x 6m wide x 6.2m deep launch pit, 6m long x 6m wide x 7.9m deep reception pit
G6 (B188 Orsett)	19.82m to 20.75m (AOD)	16.82m (AOD) (calculated)	563945	181737	563934	181755	1200mm	1450mm		Installation of a high pressure gas pipeline Unique works located at Green Lane, B188 High

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										Road, Brentwood Road & A13 Construction of launch and reception pits Open cut deep dig installation circa 160m length (Green Lane) • 12m wide x 5m deep x 160m length Construction of tunnel via micro-TBM circa 60m length (Brentwood Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 50m length (B188 High Road) • 15m long x 6m wide x 7.2m deep launch pit, 6m long x 6m wide x 6.8m deep reception pit Construction of tunnel via micro-TBM circa 90m length (A13) • 15m long x 6m wide x 6.2m deep launch pit, 6m long x 6m wide x 7.9m deep reception pit

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
G7	10.06m to 8.58m (AOD)	5.36m (AOD) (calculated)	562533	182014	562713	182068	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north of Green Lane Construction of tunnel via auger bore (assumed) 100m of 190m length • 15m long x 6m wide x 6m deep launch pit, 6m long x 6m wide x 6m deep reception pit
G10 (M25)	63m to 60m (Google Earth interpolation)	56.625m (AOD) (calculated)	557813	189568	557881	189642	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a high pressure gas pipeline Unique works located north of M25 J29 Construction to cross M25: • 15m diameter launch pit 10m depth • 5m diameter reception pit 5m depth • Installation of pipeline via micro-TBM circa 120m length
MU72 (Tilbury Railway Line)	19m to 20m (Google Earth interpolation)	9.9m (AOD) (calculated)	557983	185266	558025	185285	1200mm	1450mm	Herrenknecht AVN Machine or Similar.	Installation of a water pipeline Unique works located north of Ockenden Road Construction to cross railway line:

Works No.	Existing ground level above tunnel	Tunnel Axis Level (assumed)	Start point (Easting)	Start point (Northing)	End point (Easting)	End point (Northing)	Diameter of the tunnel (assumed)	Diameter of the micro-TBM (assumed)	Type of TBM	Description of works
										• 10m diameter launch pit 11m depth • 5m diameter reception pit 11m depth • Installation of pipeline via pipejack circa 80m length Assumed pipejack depth circa 9-10m depth under railway

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