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Address:
Noahs Ark, Cuckoofield Lane, Bracon Ash,
Norfolk NR14 8EJ

Appendix F

Ground Settlement Assessment



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Settlement Assessment

1.1 Parameters

Block E1 is located adjacent to the safeguarded Crossrail 2 tunnel alignment, as shown in Figure 1 below.

The critical horizontal distances between the proposed Block E1 development and the centre lines of the two Crossrail 2 running tunnels have been taken from the current Crossrail 2 overlay drawing. The minimum horizontal distances from the Block E1 footprint to the respective tunnel centre lines are approximately **27.0 m** and **33.1 m**.

These dimensions have been adopted for the ground movement assessment presented in the following sections.

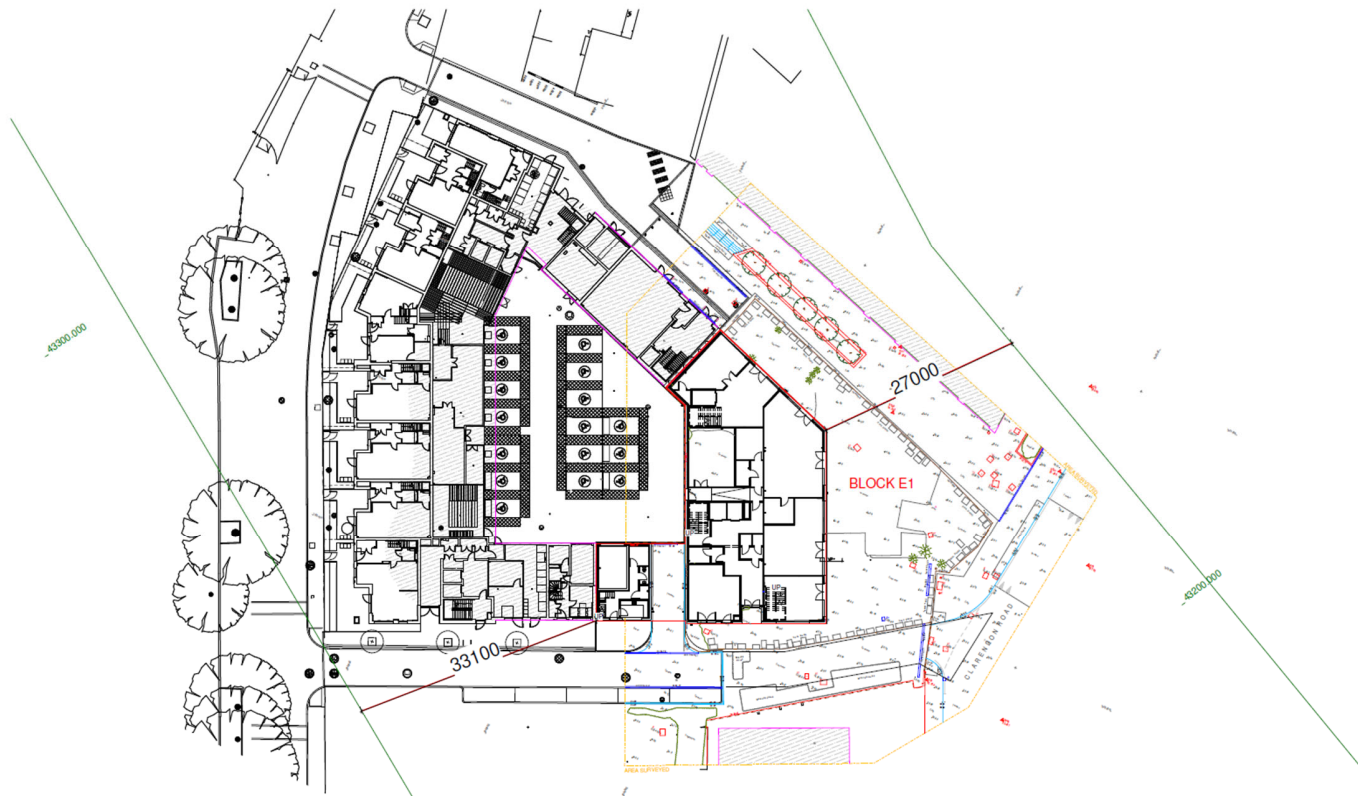


Figure 1 – Plan showing critical horizontal distances from Block E1 to the centre lines of the proposed Crossrail 2 tunnels



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1.2 Settlement assessment

The following settlement assessment is based on the method set out in Appendix A of Crossrail 2 Information for Developers, April 2021.

- **Tunnel excavated diameter, D:** 7.8 m, as specified in the Crossrail 2 Information for Developers guidance.
- **Tunnel centreline depth, z:** 25.0 m. Indicative depth advised by TfL / Crossrail 2 Safeguarding and adopted as the tunnel centreline depth for the purposes of this assessment.
- **Volume loss, VI:** 1.2%. Crossrail 2 Information for Developers.
- **Ground coefficient, K:** 0.5, adopted for London Clay / cohesive soil in accordance with the Crossrail 2 Information for Developers guidance.
- **Horizontal offset to running tunnel 1:** 27.0 m
- **Horizontal offset to running tunnel 2:** 33.1 m
- **Maximum screw pile length:** 12.0 m. Preliminary foundation design envelope.
- **Building width perpendicular to tunnel alignment:** 25.0 m
- **Building height, H:** 22.0 m

Settlement trough width parameter

$$i = K \times z$$

$$i = 0.5 \times 25.0 = 12.50 \text{ m}$$

Appendix A, Section 2.1, Equation 4.

Practical settlement trough limit

$$2.5i$$

$$2.5i = 2.5 \times 12.50 = 31.25 \text{ m}$$

Assessment extent in accordance with Appendix A, Section 3.1.

Tunnel excavated area

$$A_t = \pi D^2 / 4$$

$$A_t = \pi \times 7.8^2 / 4 = 47.78 \text{ m}^2$$

Circular tunnel geometry.

Settlement trough volume

$$V_s = VI \times A_t$$

$$V_s = 0.012 \times 47.78 = 0.573 \text{ m}^3/\text{m}$$

Appendix A, Section 2.1.

Vertical settlement

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



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Maximum Vertical Settlement

$$S_{max} = V_s / (\sqrt{2\pi} \times i)$$

$$S_{max} = 0.573 / (\sqrt{2\pi} \times 12.50)$$

$$S_{max} = 0.01830 \text{ m} = 18.30 \text{ mm}$$

Appendix A, Section 2.1.

Vertical settlement – Tunnel 1

$$S_{v1} = S_{max} \times \exp[-y^2 / (2i^2)]$$

$$S_{v1} = 18.30 \times \exp[-27.0^2 / (2 \times 12.5^2)]$$

$$S_{v1} = 1.78 \text{ mm}$$

Vertical settlement – Tunnel 2

$$S_{v2} = S_{max} \times \exp[-y^2 / (2i^2)]$$

$$S_{v2} = 18.30 \times \exp[-33.1^2 / (2 \times 12.5^2)]$$

$$S_{v2} = 0.55 \text{ mm}$$

$$S_{v, \text{total}} = S_{v1} + S_{v2}$$

$$S_{v, \text{total}} = 1.78 + 0.55 = 2.33 \text{ mm}$$

Predicted vertical settlement at the nearest edge of Block E1.

Horizontal settlement

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

$$S_h = (V_s \times y / (\sqrt{2\pi} \times K \times z^2)) \times \exp[-y^2 / (2 \times K^2 \times z^2)]$$

For Tunnel 1:

$$S_h = (0.573 \times 27.0 / (\sqrt{2\pi} \times 0.5 \times 25.0^2)) \times \exp[-27.0^2 / (2 \times 0.5^2 \times 25.0^2)]$$

$$S_h = 0.00192 \text{ m} = 1.92 \text{ mm}$$

For Tunnel 2:

$$S_h = (0.573 \times 33.1 / (\sqrt{2\pi} \times 0.5 \times 25.0^2)) \times \exp[-33.1^2 / (2 \times 0.5^2 \times 25.0^2)]$$

$$S_h = 0.00073 \text{ m} = 0.73 \text{ mm}$$

Appendix A, Section 2.2.



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Location	Tunnel offset y (m)	Vertical settlement Sv (mm)	Horizontal movement Sh (mm)
Point A - Tunnel 1	27.00	1.776	1.918
Point A - Tunnel 2	33.10	0.549	0.727
Point A - combined	-	2.325	2.645
Point B - Tunnel 1	31.25	0.804	1.005
Point B - Tunnel 2	37.35	0.211	0.315
Point B - combined	-	1.015	1.320

Combined vertical settlement at the nearest Block E1 edge = 2.33 mm.

1.3 Building strain assessment

The building strains are assessed by treating the affected part of Block E1 as a deforming idealised beam in accordance with Appendix A of the IFD.

- **Building height, H:** 22.0 m
- **Ratio of Youngs: Shear modulus ratio, E/G ratio:** 2.6, as recommended in the IFD, Appendix A, page 23.
- **Settlement trough limit, 2.5i:** 31.25 m from tunnel centreline
- **Nearest Block E1 edge:** 27.0 m from tunnel 1 centreline
- **Relevant affected building span, L:** 31.25 - 27.0 = 4.25 m
- **Zone:** The relevant 4.25 m affected span is assessed as a hogging zone

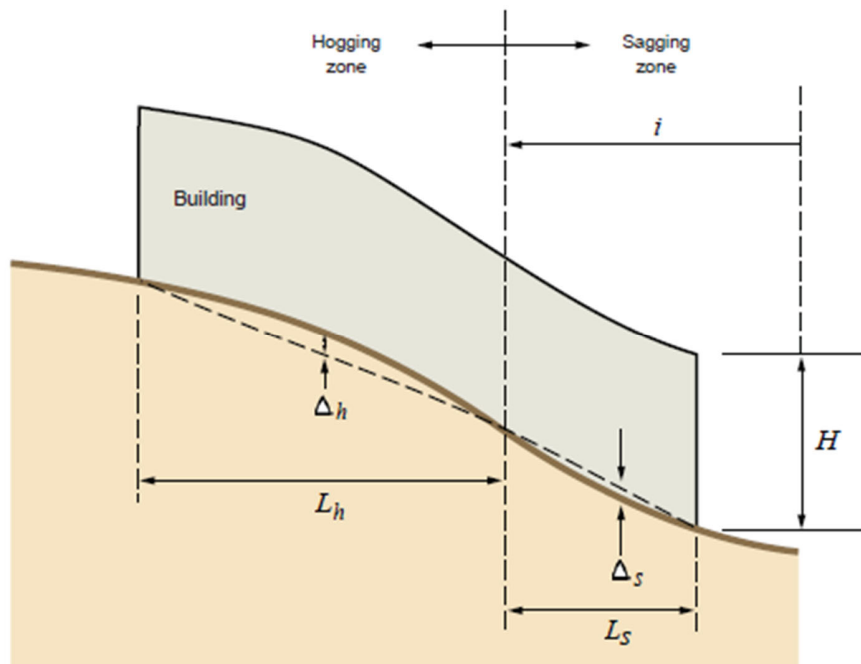


Figure 2 – Sagging and hogging zone lengths

For the hogging zone:

$$I = H^3 / 3 = 22^3 / 3 = 3549.3 \text{ m}^3$$

$$t = H = 22.0 \text{ m}$$



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The average horizontal tensile strain over the relevant affected span is:

$$\epsilon_h = (Sh_A - Sh_B) / L$$

$$\epsilon_h = (2.645 - 1.320) / 4250 = 0.000312 = 0.0312\%$$

The maximum relative deflection, Δ , is obtained numerically from the combined settlement profile over the 4.25 m affected span. The maximum deviation from the straight line joining the two span ends occurs at approximately $x = 2.04$ m:

$$\Delta = 0.113 \text{ mm}$$

$$\Delta / L = 0.113 / 4250 = 2.65 \times 10^{-5}$$

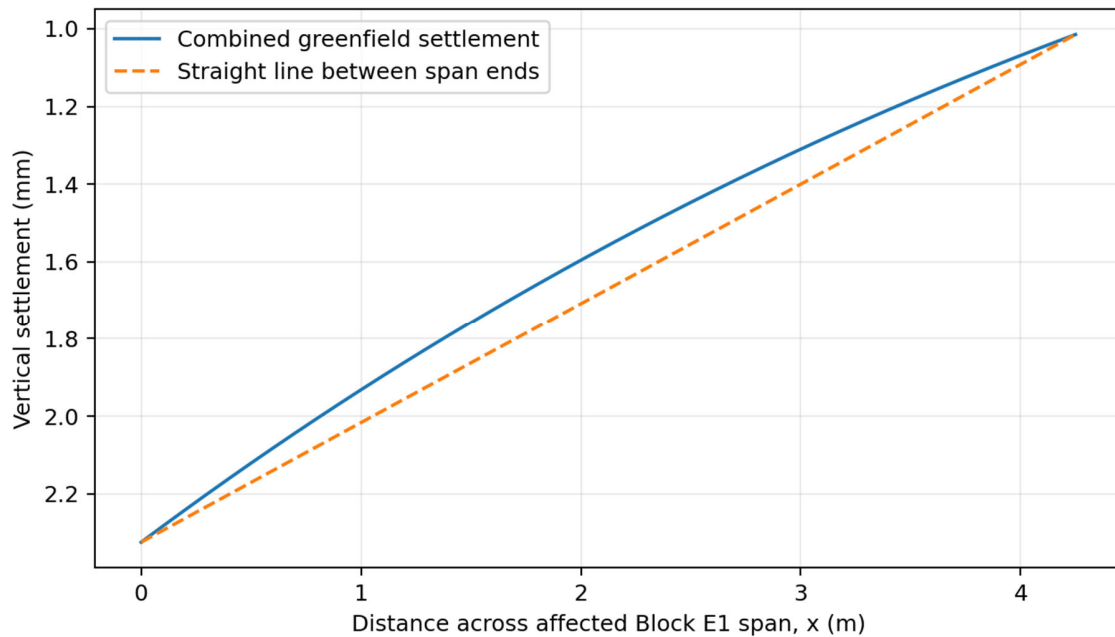


Figure 3 Combined settlement profile across the affected Block E1 span

Bending and diagonal strains

The maximum bending strain and diagonal strain are determined by rearranging Equations 13 and 14 of Appendix A, Section 3.2 of the IFD.

$$\Delta/L = [L/(12t) + (3I/(2tLH))(E/G)] \epsilon_b$$

$$\epsilon_b = 3.93 \times 10^{-6} = 0.000393\%$$

$$\Delta/L = [1 + (HL^2/(18I))(G/E)] \epsilon_d$$

$$\epsilon_d = 2.64 \times 10^{-5} = 0.00264\%$$

The horizontal strain is combined with the bending and diagonal strains using Equations 15 and 16 of Appendix A:

$$\epsilon_{bt} = \epsilon_h + \epsilon_b = 0.000316 = 0.0316\%$$

$$\epsilon_{dt} = 0.35\epsilon_h + \sqrt{[(0.65\epsilon_h)^2 + \epsilon_d^2]} = 0.000313 = 0.0313\%$$



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Assessment item	Result
Combined vertical settlement at Point A	2.325 mm
Average horizontal tensile strain, ϵ_h	0.0312%
Bending strain, ϵ_b	0.000393%
Diagonal strain, ϵ_d	0.00264%
Combined bending tensile strain, ϵ_{bt}	0.0316%
Combined diagonal tensile strain, ϵ_{dt}	0.0313%
Governing tensile strain	0.0316%

The governing maximum tensile strain is 0.0316%. This is below the 0.05% limiting tensile strain for Damage Category 0. The predicted degree of damage is therefore Class 0: Negligible.

Table 1 - Classification of visible damage

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	1	0.05–0.075
2 Slight	Cracks easily filled. Redecoration probably required. Several slight fractures showing inside of 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.	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	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 bearings, 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.			

Reference: Crossrail 2 Information for Developers, Appendix A, Table 1 (after Burland, Broms and de Mello, 1977; Boscardin and Cording, 1989).