PLAXIS analysis of a basement excavation in central London

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Excavation of a new 6 m deep basement was required as part of the development of a city centre site in London. The proposed excavation was within a very congested former car park area and would take place immediately adjacent to a row of 5 storey Georgian town houses, many of which were founded on shallow strip footings. In order to demonstrate that the proposed method of basement excavation would have a negligible effect on the existing properties a detailed Finite Element (FE) analysis of the various stages of basement construction was undertaken. This allowed action levels to be set for monitoring and provided the necessary assurance to the owners of adjacent properties.

Construction in city centre locations brings with it a host of additional challenges for the geotechnical engineer. Sites are typically compact with little space for operating plant or storing materials and surrounding roads are often congested. In order to maximise developable space new structures often extend to the edge of the development site and in close proximity to existing foundations and services for which little information is often available. New development must not only avoid these existing structures but must also limit ground movements to acceptable levels to prevent damage.

These various constraints to development are nowhere more prevalent than in central London. When a developer decided to construct a new property with a deep basement on a congested site in Victoria all of the above constraints were present (Figures 1 & 2). The site was located to the rear of Georgian properties dating from the early part of the 19th Century. The masonry and brick construction of these properties combined with their generally shallow foundations made them particularly sensitive to ground movement and so it was necessary to develop a robust methodology for the construction of the new basement.

In order to validate the proposed construction methodology FE modelling was undertaken using PLAXIS 2D V9.01 for each construction stage to confirm foundation movements of existing properties would be acceptable and to allow action levels for monitoring to be set.

Construction methodology

In order to minimise ground movements adjacent to deep excavations at sensitive sites it is common to utilise a top down construction process which provides a high level of wall restraint during excavation. Prior to excavation the perimeter wall is constructed and then progressively propped by construction of the permanent internal slabs as excavation progresses. This technique was proposed at the Victoria site using a perimeter contiguous piled wall composed of 450 mm diameter piles at 600 mm centres extending to a depth of 7 m providing a minimum toe beneath the deepest section of excavation of 1.05 m (Figures 3 & 4).

The proposed construction sequence comprised the installation of permanent slabs at three levels; ground floor, basement floor and swimming pool floor, following the sequence below;

1. underpinning of the existing 3rd party boundary wall (Figure 5)
2. installation of permanent and temporary piles
3. excavation to1m below finished ground floor slab level
4. construction of the ground floor slab
5. excavation to 0.2m below the lower ground floor slab level
6. construction of the lower ground floor slab
7. excavation to 0.2m below the swimming pool floor slab (maximum excavation depth of 6.25m)
8. construction of the swimming pool floor slab

Figure 1: Congested central London site

Figure 2: Basement excavation was to take place adjacent to existing Georgian properties

Ground conditions

Available site specific ground investigation indicated the site to be underlain by clayey sand Made Ground overlying the Kempton Park Terrace Gravels (present as a gravelly sand). London Clay was present just below the proposed pile toe level. Groundwater was recorded at the base of the Terrace Gravels. The soil profile is summarized below in Table 1. A hydrostatic ground water distribution was assumed beneath a level of -1.3 mAOD (below base of excavation at 0.25 mAOD) based on the results of long term monitoring in a number of ground water monitoring instruments at the site. In situ testing was limited to the undertaking of Standard Penetration Tests (SPTs) in boreholes with no direct measurement of soil stiffness undertaken. The shear strength properties of soils were estimated from relationships with design SPT profiles, however this crude process was not considered appropriate for the estimation of appropriate soil stiffness parameters. Initial large strain stiffnesses associated with first time loading were estimated using the empirical relationships provided in CIRIA report R143 (ref 1) for both worst credible (WC) and most probable (MP) values of SPT N. These values were then adjusted for the increased

Name	Depth to base of stratum (mbgl)	Level of base of stratum (mAOD)
Fill	2	4.2
Terrace Gravels	8	-1.8
London Clay (assumed in model)	16.2	-10

Ground level = 6.2 mAOD Ground water level = -1.3 mAOD

Table 1: Design soil profile

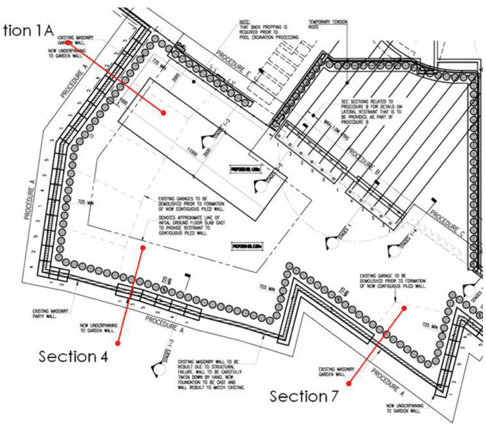

Figure 3: Site layout and cross sections analysed

Parameter	Symbol	Fill	Terrace Gravels	London Clay	Unit
Material Model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Type of behaviour	-	Drained	Drained	Drained*	-
Coefficient of at rest earth pressure	K_0	0.45	0.37	1.5	-
Unsaturated weight	γ_{unsat}	18	21	19.8	kN/m³
Saturated weight	γ_{sat}	20.5	23	19.8	kN/m³
Permeability x direction	k_x	0	0	0	m/d
Permeability y direction	k_y	0	0	0	m/d
Stiffness (moderate strain unloading)	E	WC=8,000 MP=18,000	WC=75,000 MP=140,000	WC=50,000 MP=100,000	kN/m²
Poisson's ratio (unloading)	υ	0.15	0.15	0.495	-
Cohesion	c	0.2#	0.2#	100	kN/m²
Friction angle	ϕ	33	39	0	°
Dilatancy angle	ψ	3	9	0	°
Interface strength reduction	R_{inter}	0.8	0.8	0.7	-

* undrained behaviour of the London Clay to represent ground response to short term excavation has been modelled using an undrained total stress analysis (ref. Plaxis 2D materials model manual Section 2.7) with the material behaviour set to drained in conjunction with undrained soil parameters
# a small cohesion applied to avoid complications in obtaining a numerical solution
WC = worst credible
MP=most probable

Table 2: Soil parameters used for analysis

stiffness associated with unloading behavior and reduced strain level (0.01-0.1%) following published guidance (refs 2 & 3) to provide input values for analysis. The proposed soil stiffness values were compared to published values for similar soils at nearby sites in order to confirm their appropriateness. The input values adopted for analysis are presented below in Table 2.

Analysis

Analysis was undertaken using PLAXIS 2D V9.01, modelling soil behavior using the Mohr-Coulomb failure criterion with granular fill and Terrace Gravels considered as drained and the underlying London Clay as undrained (as only the short term displacements during construction were to be determined). Analysis was undertaken as a series of drained construction stages and as such no consolidation analysis was required to calculate intermediate pore water pressures.

The strip foundations of existing properties were modelled as fully flexible to prevent soil from "hanging up" and giving a false reduction in true settlement. Piles were modelled as plate elements and floor slabs as fixed end anchors.

Loadings from 3rd party properties were applied as a combination of floor UDL and wall line load. The problem geometry was meshed using 15 noded triangular elements with local mesh refinement to the piled wall (Figure 6).
Three critical cross sections (Figure 3) through the proposed basement excavation were analyzed using both worst credible (WC) and most probable (MP) soil stiffnesses in order to determine a range of likely settlement magnitudes. Ground movements due to the application of the building loads associated with existing adjacent properties were removed from the output due to the age of the buildings indicating that this settlement would now be complete.

The deformed mesh is shown in Figure 7 with vertical settlements shown in Figure 8 and horizontal displacements in Figure 9. The results of analysis are summarized below in Table 3.

Vertical displacements (mm)	section 1A		Section 4		Section 7	
Location	WC	MP	WC	MP	WC	MP
Underside of underpinned party wall	-3.8	-3.4	-1.8	-1.4	-1.9	-1.4
2m from excavation	-3.5	-2.9	-1.5	-1.1	-2.5	-1.6
5m from excavation	-2.6	-1.4	-1.2	-0.6	-1.6	-0.8
centre of excavation	9.5	4.9	8.5	4.4	8.4	4.4

Vertical displacements (mm)	section 1A		Section 4		Section 7	
Location	WC	MP	WC	MP	WC	MP
Pile head (positive = into excavation)	1.4	1.2	0.4	0.36	0.5	0.4
Mid prop (positive = into excavation)	4.2	3.25	1.8	1.3	1.4	1.3

Table 3: Summary of ground movements

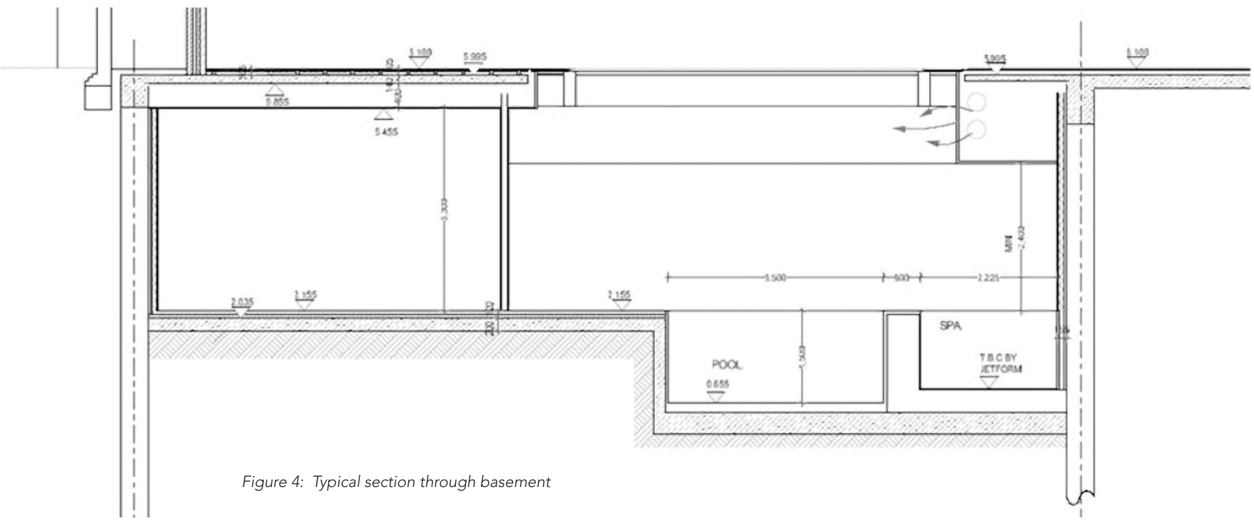

Figure 4: Typical section through basement

Figure 5: Underpinning of existing foundations

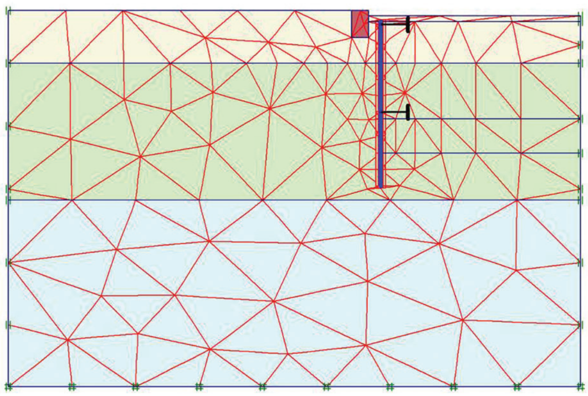

Figure 6: FE mesh

Discussion

There are two subtle features of the FE modelling that are worthy of note. Firstly, the pre-loading effect of imposing the adjacent building loads on the sub-soil results in very slightly reduced settlements beneath the adjacent buildings when compared to the ground immediately beyond them.

Secondly, the settlements immediately behind the wall are slightly reduced due to the combined effect of a slight unloading due to the excavation of ground between the piled wall and the 3rd party wall and the effect of the interface elements modelling the soil structure interaction between the piles and the adjacent soil locally increasing vertical stiffness.

The results of the analyses carried out indicated that in all cases ground settlements adjacent to the basement excavation were less than 5 mm. This confirmation that anticipated settlements were to be very small provided reassurance to the adjacent homeowners. Monitoring of structural movements was undertaken with action levels of 3 mm and 5 mm set corresponding to increased frequency of monitoring and halt of excavation works respectively.

Conclusions

PLAXIS analysis provided the necessary confidence to undertake deep excavation close to sensitive buildings in a city centre location and set monitoring action levels. Following the successful construction of the deep basement at the study site work has commenced nearby on the new North Ticket Hall being constructed as part of improvements to the London Underground Victoria station.

This excavation is also to be constructed using a top down technique, however due to the greater depth and penetration beneath the ground water table a secant wall is to be constructed which will toe into the low permeability underlying London Clay.

The Company

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References

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- Atkinson, J.H. (2000) Non linear soil stiffness in routine design. Geotechnique, vol 50, no 5, pp487-508.
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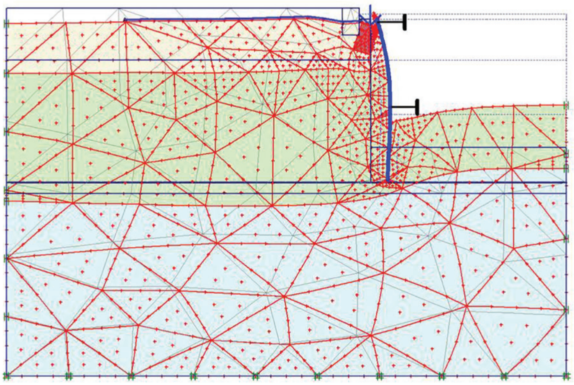

Figure 7: Deformed mesh at section 1A Stage 7

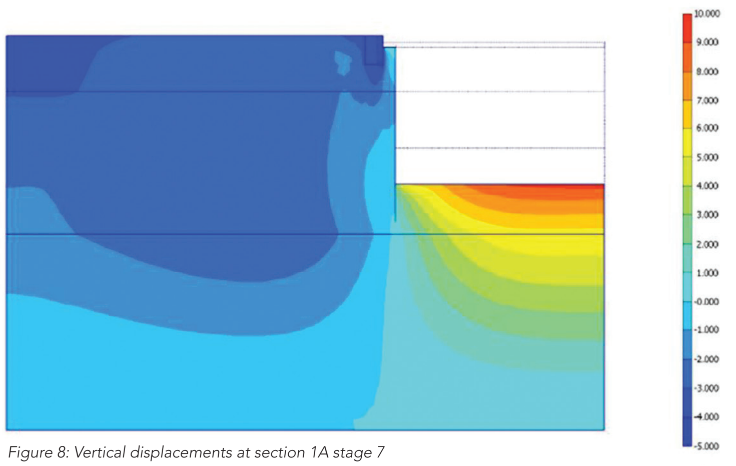

Figure 8: Vertical displacements at section 1A stage 7

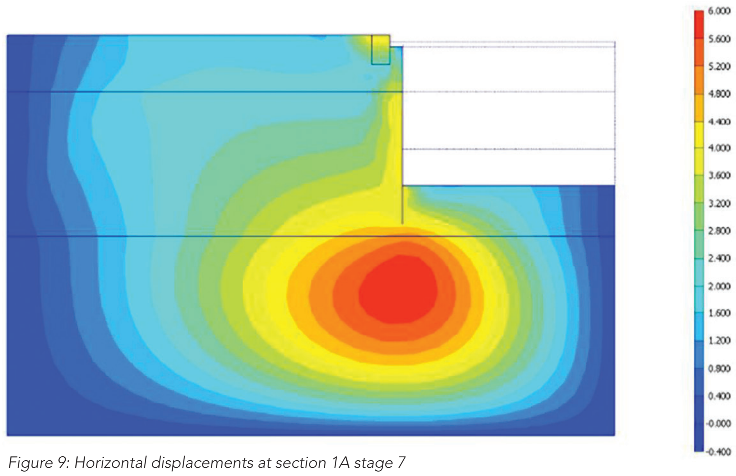

Figure 9: Horizontal displacements at section 1A stage 7