TBM PEANUT – SHAPED SHAFT OF SILVERTOWN TUNNEL PROJECT

Pozo multicelular para TBM del proyecto del Túnel de Silvertown

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RESUMEN

Los pozos multicelulares son una solución eficiente frente a los pozos estándar soportados por anclajes y puntales, especialmente en excavaciones de gran tamaño y profundidad. Los pozos circulares, debido a su mayor rigidez, presentan menores deformaciones, reduciendo los desplazamientos del terreno y minimizando el impacto en estructuras circundantes. Este pozo fue empleado para el lanzamiento de la TBM para un túnel vial de 1.4 km. Está conectado al pozo rectangular de recepción de la TBM y se compone de cuatro pozos circulares secantes de 21.2 m de diámetro. Su profundidad, medida hasta la base de la losa inferior, varía entre 24.6 y 19.9 m, con una losa inclinada que sigue la pendiente del túnel.

ABSTRACT

A multicell shaft, also known as a peanut-shaped shaft, offers an efficient alternative to standard box shafts supported by anchors and struts for large, deep underground excavations. Circular shafts generally exhibit greater stiffness, resulting in reduced wall deflection, minimized ground movement, and a lower impact on the surrounding structures. This multicell shaft served as the TBM launch chamber for a 1.4 km road tunnel. It is connected to a rectangular shaft for TBM reception and comprises four circular secant shafts with a diameter of 21.2 m each. The shaft depths, measured to the bottom of the temporary base slab, range from 24.6 to 19.9 m, with the base slab inclined to match the tunnel's gradient.

PALABRAS CLAVE: TBM multicell shaft, hydraulic struts, 3D models of underground structures.
KEYWORDS: pozo multicelular para TBM, puntales hidráulicos, modelos 3D de estructuras subterráneas.

1. Project description

The Silvertown Tunnel is a new 1.4km twin-lane road tunnel under the River Thames, connecting the Greenwich Peninsula with West Silvertown. The peanut-shaped shaft served as the Launch Chamber (LCH) for the Tunnel Boring Machine (TBM) used to construct the tunnel. This shaft was located on the Silvertown side of the river, adjacent to the Retrieval Chamber (ReCH) and at the start of the Cut & Cover (C&C) tunnels.

Project details:

- Client: Transport for London (TfL)
- Construction Joint Venture (CJV): Riverlinx (Ferrovial, BAM Nuttall and SK-Ecoplant)
- TBM Chambers Designer: Ayesa

The use of a multicell shaft as the Launch Chamber was proposed by Riverlinx, with Ayesa responsible for developing the complete design, from feasibility study to detailed design.

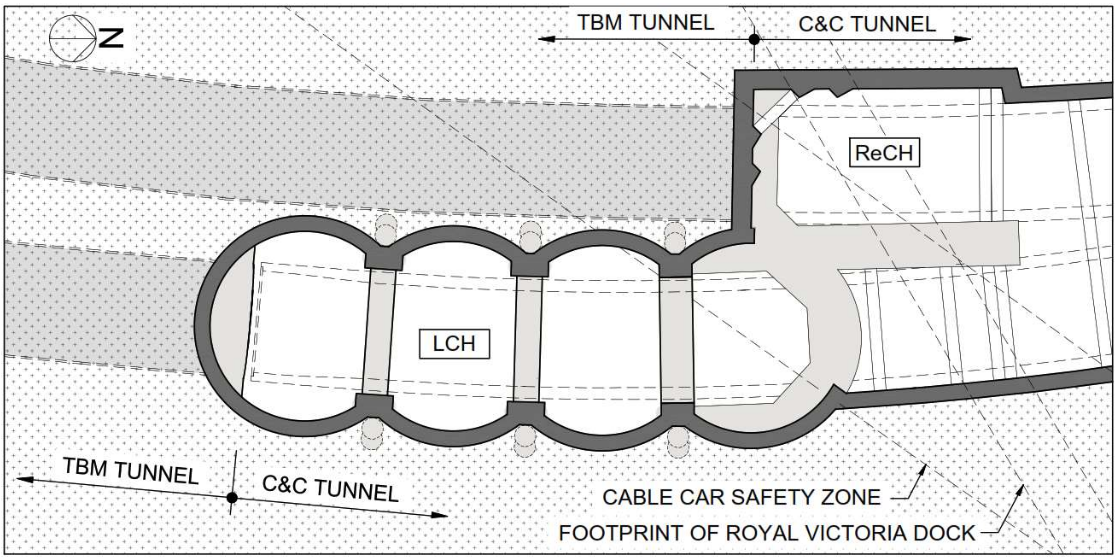

Figure 1. Plan view of the Launch and Retrieval Chambers.

2. Geometry and structural elements

The Launch Chamber, a multicell shaft, comprised four circular secant shafts with a diameter of 21.2 m, constructed using 1300 mm nominal diameter Hard-Hard secant bored piles (Figure 1). The shaft depths, measured from the ground level to the bottom of the 0.7–1.2 m thick temporary base slab, ranged from 24.6 m at the interface with the Southbound TBM tunnel to 19.9 m at the interface with the Retrieval Chamber. Consequently, the base slab was inclined to match the tunnel's slope. The length of the secant bored piles (including the capping beam) was 29.3 m.

At the intersections between shafts, T-shaped counterforts were installed to withstand the loads transmitted by the shafts. The length of the counterforts was 33.3 m for counterfort C1 and 29.3 m for counterforts C2 and C3. Additionally, two levels of transverse beams connected opposite counterforts, forming rigid portal structures. During the excavation, temporary preloaded hydraulic/hybrid steel struts (MP750) were installed beneath the transverse beams. After casting the concrete base slab, the struts were sequentially removed from top to bottom.

During construction, two large openings were made in the LCH structure, at both ends: the first opening was the Shaft 1 – Soft-eye opening, produced during the TBM break-in operations; the second opening was the Shaft 4 – Retrieval Chamber opening, to allow for C&C tunnel permanent structure construction including cross-passage CP8, which currently links the Southbound and Northbound tunnels.

The shafts dimensions were determined based on the inner space between counterforts, ensuring adequate spaceproofing for:

- TBM "Jill", featuring a cutter head diameter of 11.91 m (the largest TBM in the UK) and a weight of 1800 t.
- Width of the C&C tunnel.
- Construction tolerances of the counterforts.
- Conveyor belt used in tunnel operations.
- Northbound TBM tunnel after the U-turn, passing next to Launch chamber.

The LCH was a temporary structure designed to function during TBM operations and the construction of both the bored and C&C tunnels. Upon completing the C&C tunnel within the chamber, the structure was backfilled, and the ground level was restored.

The bored pile technology was requested by the CJV, driven by the challenges presented by the subsurface conditions in the former industrial zone, including the presence of obstacles and the need to bore through the backfilled Royal Victoria Dock.

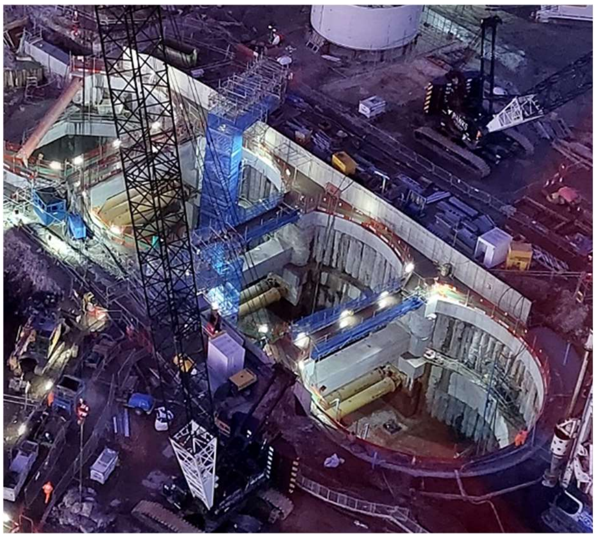

Figure 2. Construction of the Launch chamber.

2.1 Secant piles

The LCH walls were constructed using 1300 mm diameter Hard-Hard secant piles with varying spacings, concrete grades, and reinforcement configurations across the shafts to meet specific project requirements. Key design challenges included:

- Piles located in the Shaft 1 – Soft-eye opening required a concrete strength lower than C25/30 and GFRP reinforcement due to the TBM breakthrough operations.
- Positional and verticality tolerances reduced the contact area between intersecting piles, impacting the wall's ability to resist hoop forces.

Of the Hard-Hard piles forming the wall, only secondary piles were reinforced. To facilitate internal dewatering, the embedment length of the piles extended into the impermeable Lambeth Group strata.

The installation of the piles was carried out using a temporary casing to support the soil during the drilling. For primary piles, the casing depth was optimized to seal 1 m into the London Clay layer.

2.2 Counterforts

Counterforts, situated at the intersections of the shafts, were the most challenging construction elements as they needed to resist the full hoop force coming from the walls. Their structural balance was achieved through multi-level struts, including transverse beams and temporary hydraulic/hybrid struts.

The main characteristics defining the counterforts were the following:

- T-shaped borehole formed by six 2.2 m OD bored piles with casing.
- Reinforcement cages measuring 33 m / 29 m in length, divided into three sections.
- Circa 70 tons of reinforcement per cage.
- Designed to withstand the load transferred from the circular shafts.
- Shoring system comprised by transverse concrete beams and hydraulic struts installed progressively during excavation.

For the construction of the counterforts, the concurrent excavation of the six piles was required to fit the T-shaped reinforcement cage. Thus, soft piles were executed around the perimeter up to the London Clay, and fluid polymer was used from the base of the London Clay to the toe level of the counterforts to stabilize the opening and control the deviation.

The T-shape design was selected to provide robust support for the secant pile walls while accounting for construction tolerances. A key consideration during execution was reducing the reinforcement cage weight to facilitate lifting operations. This was achieved by:

- Dividing the reinforcement cage into three sections, pre-assembled off-site and connected on-site.
- Using a combination of standard carbon steel and high-strength steel.

2.3 Temporary hydraulic/hybrid struts

The struts installed between the counterforts, supplied by GFS for this project, were all MP750 "hybrid" struts. The MP750 represents the highest load-carrying capacity within the GFS range, with a capacity of 11,700 kN. These struts were selected for their benefits, including hydraulic actuation and the safety provided by twin mechanical load-bearing screws.

For the Launch Chamber, a total of 26 struts were installed between the counterforts (Figure 4). Once the excavation was carried out up to 0.5 m below each level of struts, the surface of the counterforts was straightened, steel waler beams were placed and struts were installed with preloading. The pre-stressing operation was performed sequentially at each support level to ensure uniform distribution of pre-stress force across all struts.

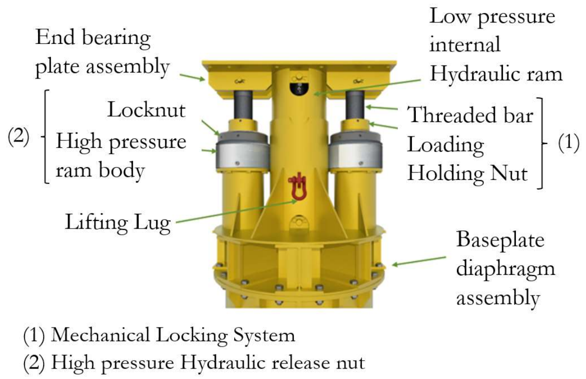

Figure 3. MP750 components identification.

Upon completion of the excavation and base slab installation, the struts were removed in a top-down sequence. The removal process involved a cycle of de-pressurization, where the load on individual struts was gradually released in phases. Throughout this process, load increases in the remaining struts were closely monitored to prevent overloading and ensure the safety of the system.

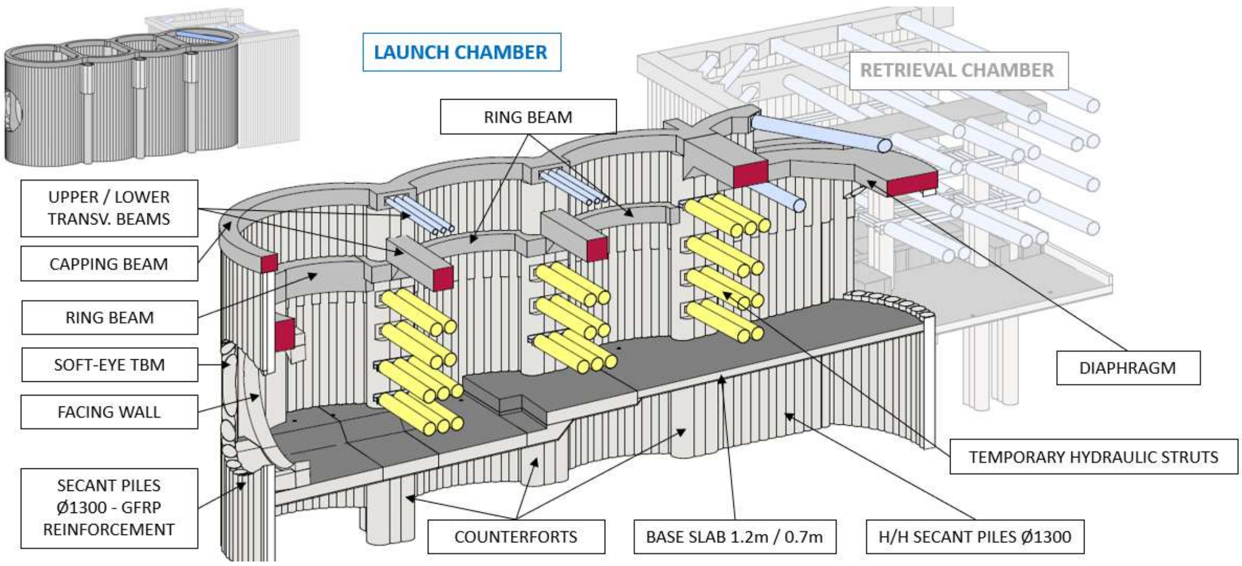

Figure 4. Launch and Retrieval Chamber, 3D view.

3. Ground conditions and hydrology

The site was underlain by Made Ground, Alluvium, and River Terrace Deposits resting above the London Clay Formation, with this overconsolidated clay constituting most of the excavated material. Below the London Clay lay the Harwich Formation, Lambeth Group strata, Thanet Sand, and Chalk.

The site's hydrogeology comprised three aquifers (upper, intermediate, and lower) with varying groundwater levels. In the upper aquifer, the groundwater table was located near ground level, whereas the intermediate and lower aquifers exhibited slightly lower water levels, influenced by historical pumping [1].

These aquifers are separated by two aquicludes: the London Clay Formation and the Lambeth Group Shelly Beds. The thickness of these formations varied significantly across the site, particularly the Shelly Beds, which were generally relatively thin. This limited thickness allowed a small degree of hydraulic connection between the intermediate and lower aquifers, as it had been demonstrated by recent projects in East London [2].

Depressurising the intermediate and lower aquifers using dewatering wells was essential for the stability of the temporary works in the Launch Chamber. This process also allowed for a reduction in the depth and reinforcement requirements of the temporary TBM shaft base slabs.

Finally, two ground treatment areas (soft piles) were established adjacent to the Launch Chamber. These treatments were implemented by the TBM tunnel team at the TBM's entry and exit points to create cofferdams. These treated areas altered the distribution of horizontal earth pressures, further intensifying the asymmetrical loading conditions of the shafts.

4. Construction sequence

The construction sequence for the Launch Chamber was developed in accordance with the requirements established by the CJV, regarding the concurrent excavations for LCH and ReCH, TBM operations and construction of permanent C&C tunnel.

The main challenges due to the construction sequence and the key construction stages are listed below:

1. Unbalanced load due to concurrent excavation of LCH and ReCH hence Diaphragm slab executed in shaft 4 to stiffen the shaft 4 connection ReCH.
2. Installation, pre-stressing and de-pressurization operations of temporary struts were carried out in sequence at each level to ensure uniform distribution of stresses and ensure that the capacity of struts was not exceeded.
3. Base slab design to support the TBM self-weight and the Thrust Frame reactions (Thrust force 37,500 kN).
4. Heavy crane for TBM lifting operating in one of the sides of the peanut shaft thus unbalanced loads that increased the forces in the shaft walls and the counterforts.
5. TBM passing next to LCH chamber prior to the breakthrough into ReCH causing unbalanced loads on the shaft walls and the counterforts.
6. Loss of symmetry of the chamber with the openings in shafts 1 and 4. To account for this, facing wall, stiffening rings and diaphragm slabs were executed to support the structure.

5. Global analysis

5.1 Hoop force

The natural behaviour of circular shaft is to transmit lateral (horizontal) earth pressure and groundwater pressure as hoop compression along the concrete wall (see Figure 5a), without flexure of the wall, allowing an efficient utilization of the concrete section.

The same principle applies to multicellular shafts, with the addition of transverse elements to support the intersections of the circular shafts. At every intersection of a multicellular shaft, there must be a rigid vertical element, or counterfort. Opposing counterforts should be braced by transverse beams, a shoring system, or cross-walls (refer to Figures 4b and 4c). The principle of compressive pressure and hoop force is illustrated in Figure 4 for the ideal symmetrical case. However, the following considerations must be accounted for in real structures:

- Different depth of shafts.
- Openings in shafts.
- Live loads.
- Varying geological conditions.
- Connection / interaction with adjacent chamber.
- Non symmetrical excavation.

In all these cases, different hoop forces are generated in each shaft. As a result, the asymmetrical action must be restrained by counterforts. Additionally, TBM operations, such as break-in and break-out, also produce asymmetrical loads.

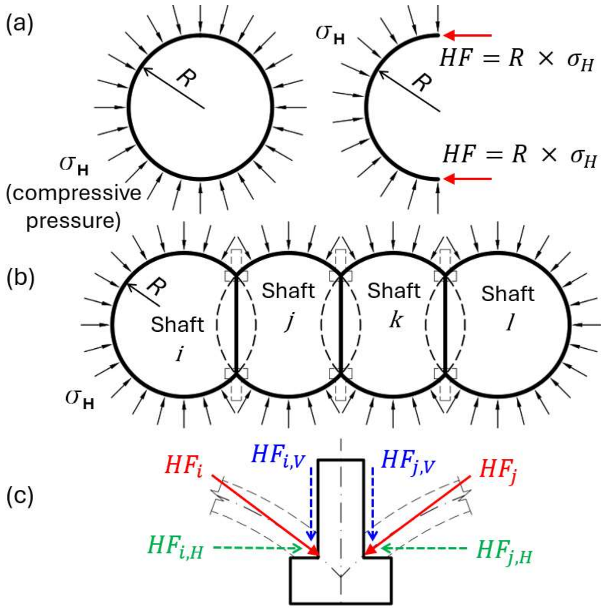

Figure 5. Hoop force: (a) Hoop force in circular shaft; (b) Symmetrical multi-cellular shaft; (c) Hoop force components acting on counterforts.

In the symmetrical case, $HF_i \approx HF_j$, thus, the horizontal components are in equilibrium, $HF_{i,H} \approx HF_{j,H}$, and the vertical components of the HF are additive, $HF_{i,V} + HF_{j,V} = HF_V$.

Finally, for the design of counterforts: HF_V must be considered along the entire height for flexure and shear in the transverse direction of the multicell shaft; ΔHF_H must be accounted for flexure and shear in the longitudinal direction; ΔHF_H and HF_V shall be used to verify torsion due to their eccentricities.

5.2 Calculation methodology

To undertake a more realistic analysis of the behaviour of the embedded peanut shaft, the following SSI calculations were performed:

i. Calculation of earth pressures and subgrade reactions in Plaxis 2D under axisymmetric / plane strain conditions, considering multiple load scenarios during excavation.
ii. Application of earth pressures into 3D structural models including both LCH and ReCH with Construction Stages analysis and flexible spring supports.
iii. Finaly, the Plaxis 3D model validated the outputs of the 2D models, contrasted the results from the structural models and provided trigger levels for the monitoring system.

In addition, to verify the wall deflections, the SLS models were developed using cracked section properties with a 50% reduction of the flexural stiffness according to CIRIA 760 [3].

The objectives of the 3D FE models for the Launch and Retrieval Chambers were as follows:

- To analyse the interaction between LCH and Retrieval chamber with effect of concurrent excavations.
- To calculate and analyse the hoop compression in semi-circular secant pile walls throughout all construction stages.
- To analyse the action of semi-circular secant piles wall on counterforts.
- To evaluate the TBM Trust force redistribution within the base slab of the peanut shafts.
- To design the facing walls around large openings in secant piles walls for TBM break in / out and large opening for C&C tunnel.

5.3 Geotechnical models

During the early phases of conceptual design, vertical cross-section models were developed in the geotechnical FEM software Plaxis 2D, assuming axisymmetric behaviour for the shafts and plane strain behaviour for the counterforts. As the design progressed, these models were used to evaluate dewatering scenarios, horizontal earth pressures acting on the retaining structures, subgrade reactions, and other critical factors.

However, the results from the 2D analyses were simplifications of the inherently 3D soil-structure interaction. To validate these models, a Plaxis 3D model was developed in the detailed design stage, incorporating the complete construction sequence of both the Launch and Retrieval Chambers, as well as all relevant load scenarios. Beyond this validation, the 3D model also served to contrast the structural results, although the structural models ultimately provided the basis for the structural design of individual elements. Finally, this model was employed to define the monitoring trigger levels for the axial loads in the struts, as well as the deflection of secant piles and counterforts.

5.3.1. Materials

The soils were primarily modelled using the Hardening Soil constitutive model, except for the Upnor Formation and Thanet Sands layers, which were modelled with a Mohr-Coulomb model due to their lesser relevance. For the cohesive materials, such as the London Clay, the selected drainage type was *Undrained A*, for which only the effective strength parameters are provided as input in the software.

Regarding the vertical retaining elements, isotropic plates were used in Plaxis 2D to represent the secant piles and the counterforts, assuming an equivalent stiffness for the later. In Plaxis 3D, the counterforts were modelled as volume elements, while the secant pile walls were represented as anisotropic plates: the bending stiffnesses in the horizontal direction was reduced to 1% of the vertical values [4].

5.3.2. Subgrade reactions

The necessity of estimating the subgrade reactions arose from the requirements of the structural models, where ground stiffness was represented using compression springs.

For the horizontal springs supporting the retaining walls, subgrade reactions were determined as follows using Plaxis 2D: after simulating the full excavation sequence, horizontal prescribed displacements were applied to the retaining element. The resulting horizontal earth pressures at the back of the element were measured and divided by the prescribed displacement to compute the average subgrade reaction for each geological unit. This process was repeated for multiple displacement values to establish a relationship between K_h (horizontal subgrade reaction modulus) and u_x (horizontal displacement).

A similar process was used to determine vertical subgrade reactions but applying vertical displacements to the base slab instead.

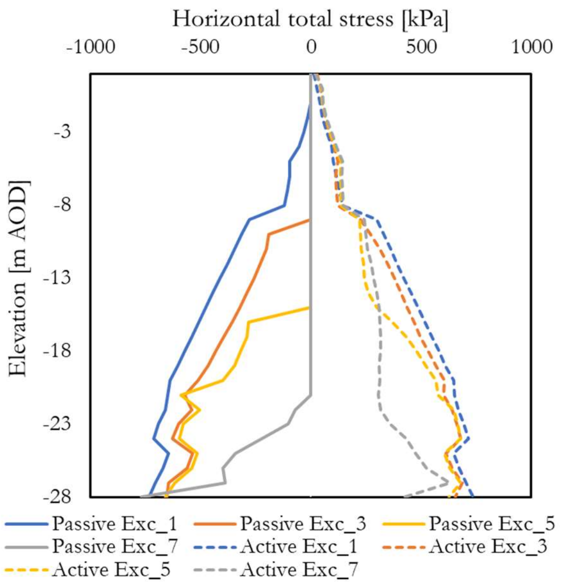

Figure 6. Horizontal total earth pressures.

5.3.3. Earth pressures

Similar to subgrade reactions, horizontal earth pressures are another critical geotechnical input required for the structural models. In this case, horizontal effective pressures on both the active and passive sides of the retaining elements were extracted from Plaxis 2D. Figure 6 shows an example of the earth pressures extracted from Plaxis and applied as an input in the structural models.

5.4 Structural 3D models

Due to the complexity of the structure, its asymmetry and the required construction sequence, the Peanut structure along with the Retrieval chamber, were modelled in 3D by means of the following three FE models.

Figure 9 shows the main results obtained from the calculation models, which illustrate the basic structural behaviour of the structure.

5.4.1. Midas Civil model

The secant bored pile wall was represented by a space frame system with an orthotropic grillage assembly, where vertical beam elements were used to represent secondary hard piles and horizontal beam elements to represent primary hard piles. The thickness of the horizontal truss elements (h) was defined equal to the length of the intersection between the secondary and the primary piles. Vertical beam elements transmitted all type of loads: flexure, shear and axial forces, whereas horizontal elements transmitted only circumferential axial forces – Hoop force. This initial 3D model was the one from which the stress results were extracted and on which the design of all the structural elements was based.

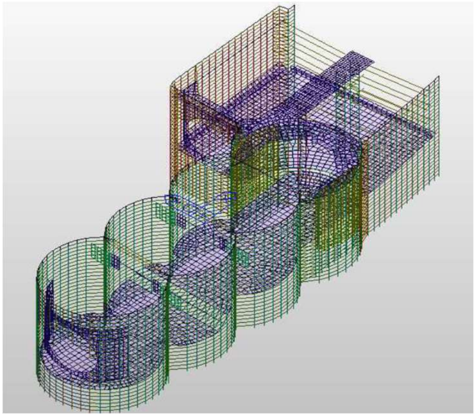

Figure 7. 3D structural model in Midas Civil.

5.4.2. Plaxis 3D model

Representation of the secant bored pile wall was done by rectangular plate elements whose geometrical and mechanical properties were defined using an equivalent plate thickness (h_{equiv}) and an equivalent Young's modulus (E_{equiv}) calculated as follows.

For the actual vertical flexural stiffness the inertia of the unreinforced primary pile was neglected and only the reinforced secondary pile was considered.

$$E_{equiv}I_{equiv} = E_{equiv} \times \frac{1}{12} b_1 \left(h_{equiv}\right)^3$$

$$E_{sec} \times \frac{1}{64} d^4 \quad \textbf{(1)}$$

where,

$E_{equiv} = Equivalent\ Young's\ Modulus$
$I_{equiv} = Inertia\ of\ 1m\ of\ wall$
$b_1 = Width\ of\ wall\ in\ the\ long.direction$
$h_{equiv} = Thickness\ o\ the\ plate\ element$
$E_{sec} = Young\ Modulus\ of\ the\ second.pile$
$d = diameter\ of\ the\ secondary\ pile$

For the horizontal stiffness both the primary and the secondary piles contribution was considered.

$$E_{equiv}A_{equiv} = E_{equiv} \times b_2 h_{equiv} =$$

$$\frac{E_{prim}A_{prim} + E_{sec}A_{sec}}{s} \times b_2 \quad \textbf{(2)}$$

where,

$b_2 = Height\ of\ the\ wall\ considered\ (1m)$
$E_{prim} = Young\ Modulus\ of\ the\ primary\ pile$
$A_{prim} = \ Primary\ pile\ area\ in\ the\ intersection$
$A_{sec} = Secondary\ pile\ in\ the\ intersection$
$s = spacing\ between\ adjacent\ second.piles$t
$E_{equiv}\ , I_{equiv}\ , h_{equiv}$ and E_{sec} $refer\ to\ above$

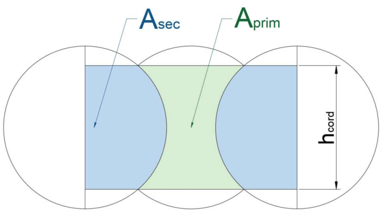

Figure 8. Area for the horizontal stiffness.

From equations (1) and (2), the expressions for the calculation of the E_{equiv} and h_{equiv} were derived:

$$h_{equiv} = \sqrt{\frac{3\pi \times s \times d^4 \times E_{sec}}{16 \times \left(E_{prim}A_{prim} + E_{sec}A_{sec}\right)}} \quad \textbf{(3)}$$

$$E_{equiv} = \frac{E_{prim}A_{prim} + E_{sec}A_{sec}}{s \times h_{equiv}} \qquad (4)$$

The model was used for the validation of the Plaxis 2D model and the comparison of outputs of Midas Civil, mainly in terms of deformations on the structure.

5.4.3. Ansys 3D model

Three-dimensional solid elements were used to model both, secondary and primary piles and the interaction between the piles was considered by means of frictional contact elements included in the intersection between them. Results from the Ansys model were compared to those obtained in the orthotropic grillage model using beams and it was proven that the behaviour and the forces provided were in both similar. That way the structural design carried out using Midas was validated.

6. Monitoring

The monitoring system for the Launch Chamber included the following instrumentation:

The hydraulic struts featured an integrated monitoring system that allowed real-time load tracking via a dedicated website. This offered several advantages: a) Each individual strut could be monitored, ensuring redundancy; b) Installation times for the instrumentation were eliminated; c) Potential installation issues caused by site conditions were avoided.

A total of 13 inclinometers were installed in the counterforts and selected piles around the shafts. Together with the strut instrumentation, these inclinometers served as the main tools to verify the safe progress of the works.

Ancillary devices such as monitoring prisms, distometers, and precise levelling points were also deployed and used to cross-check inclinometer readings.

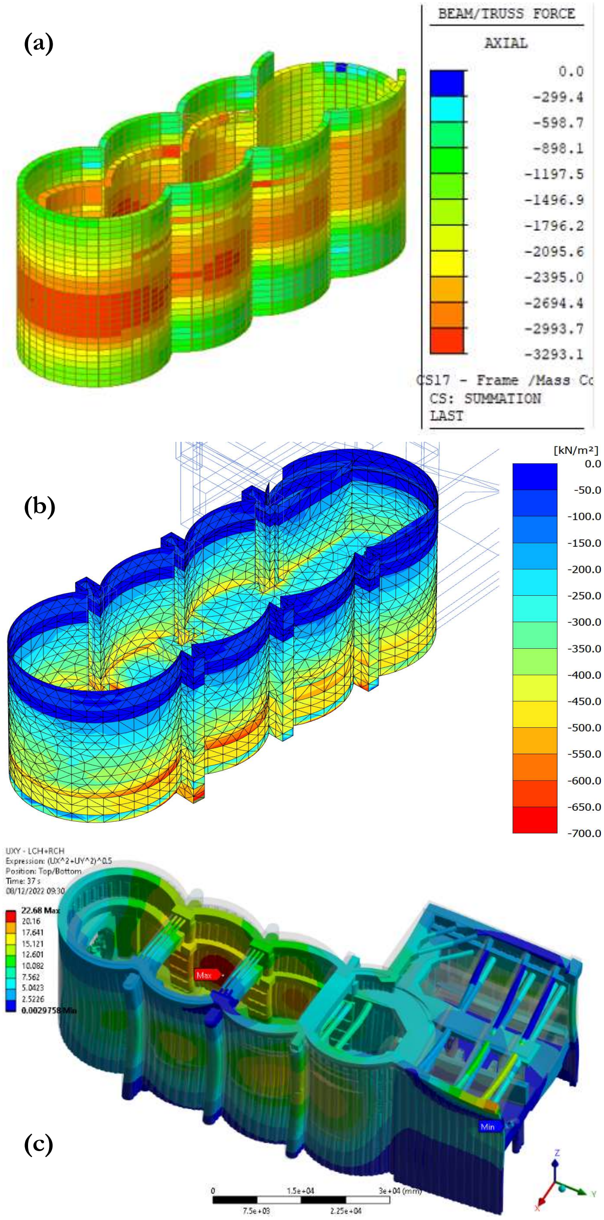

Figure 9. (a) Hoop force with completed excavation (Midas Civil); (b) Normal effective earth pressures acting on Launch Chamber structure (Plaxis 3D); (c) Displacements Uxy (Ansys 3D).

Figure 10 presents a comparison between the expected deflections of the counterforts (as predicted by Plaxis 3D) and the inclinometers data around the date in which the excavation reached the lowest level. It should be noted that the instruments data has been adjusted to align the lowest data point to that of Plaxis 3D for comparative purposes, as the inclinometers cannot capture the rigid body displacement of the counterforts. As shown, the measured data aligns reasonably well with the predicted movements, validating the design.

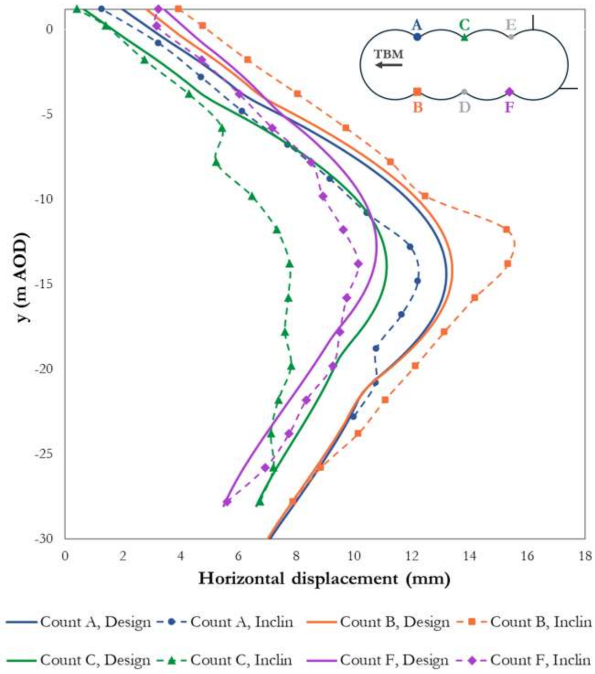

Figure 10. Comparative between predicted counterfort displacements and inclinometer data.

7. Conclusions

An efficient and innovative structure has been designed for the TBM shaft. The successful implementation of a multicell peanut-shaped design for the Silvertown Tunnel shaft enabled savings in steel strutting, pile reinforcement, and programme duration. Strut-free shafts are particularly suitable for applications requiring working space for heavy lifting, such as TBM shafts.

Around the world, various peanut-shaped shafts have been constructed using diaphragm walls and sprayed concrete. However, this project marked the first peanut-shaped shaft constructed with secant piles in the UK at the time of its completion in 2021. The multicell launch chamber shaft earned the New Civil Engineer Tunnelling Award for *Innovation in Shaft Design* & *Construction* in 2022.

Advanced numerical models were developed to address the complexity of the structure. A comparison of the numerical model results with monitoring data validated the design. Notably, the results of the 3D numerical models revealed that the outer shafts behave similarly to axisymmetric models, while the inner shafts work in flexure. Thus, plain-strain models are more appropriate for simplified analyses.

The idea of using a peanut-shaped shaft was proposed by Riverlinx, the design was developed by Ayesa.

Ayesa was also responsible for the second shaft for the TBM´s U-turn, as well as the design of the following temporary and permanent packages: Cut & Cover Tunnels, Open Cuts and the substructure for both Silvertown Tunnel Portals.

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