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Thames Tideway Tunnel: beneath the Thames tunnelling challenges and achievements

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The Thames Tideway Tunnel represents one of the most ambitious and transformative infrastructure undertakings in London's recent history. Central to the project was the construction of the main tunnel, spanning approximately 25 km across central London and engineered to capture, store and transfer combined sewer overflows to the upgraded Beckton Sewage Treatment Works through the completed Lee Tunnel. The main tunnelling operations were executed using tunnel boring machines (TBMs). This paper examines some of the technical aspects of the TBM tunnelling works, highlighting innovative approaches and best practices implemented throughout. Key areas of focus include the construction approach, the requirement for high-pressure hyperbaric interventions (which required special dispensation from the Health and Safety Executive) and the management of tunnelling operations through areas of deoxygenated ground. The paper also addresses the management of complex contractual and construction interfaces, as well as the successful transit of numerous high-profile third-party assets, including the iconic Tower Bridge. The challenges were effectively managed through coordinated engineering solutions, effective mitigation and continuous monitoring. The successful completion of the tunnelling works underscores the meticulous planning and execution that have defined the success of the Thames Tideway Tunnel project.

Keywords: hyperbaric & hypoxia; soils & ground conditions; tunnels & tunnelling; UN SDG 11: Sustainable cities and communities; UN SDG 13: Climate action

1. Introduction

Construction of the main tunnels for the Thames Tideway Tunnel project presented a unique and complex set of challenges. These included

- tunnelling deep beneath the tidal River Thames through the full geological sequence of the London Basin
- encountering ground conditions with deoxygenated ground gas
- conducting high-pressure hyperbaric interventions at levels exceeding standard UK regulatory limits
- tunnelling beneath numerous high-profile third-party assets and
- managing intricate contractual interfaces.

This paper reviews these key challenges, the mitigation strategies employed and the overall success in delivering these critical

components of the project deep beneath the River Thames in support of a cleaner, healthier river for London.

The Thames Tideway Tunnel (henceforth called 'the project') features 25 km of main tunnel and 6 km of long connection tunnels that connect to the Lee Tunnel at Abbey Mills Pumping Station, creating the 'London Tideway Tunnels' that enhance sewage infrastructure and protect the tidal River Thames from pollution. The project was divided into three main sections: west, central and east. The Lee Tunnel was successfully completed and officially opened in 2016, establishing a key link between Abbey Mills Pumping Station and Beckton Sewage Treatment Works.

The purpose of the project is to manage and control combined sewer overflow (CSO) discharges. It addresses 34 of the 57 CSOs identified by the Environment Agency, ensuring that harmful combined sewage is captured before it enters the river (see Figure 1). This system allows for the safe transfer of combined sewage to Beckton Sewage Treatment Works, protecting the river and its ecosystem.

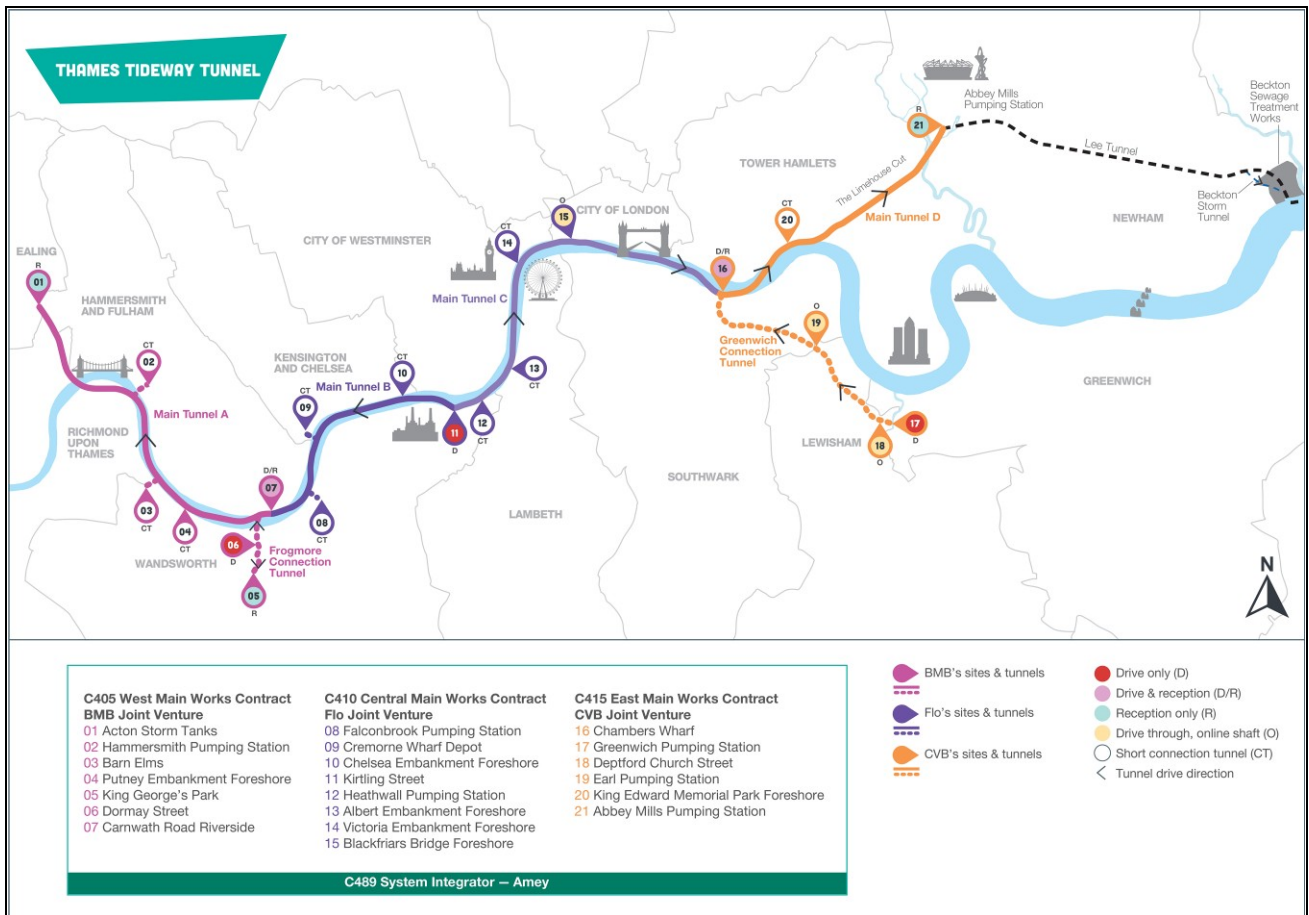


Figure 1. Overview of project sites, main works contractor areas and tunnel routes

The west section extends 7 km from Acton Storm Tanks to Carnwath Road Riverside (Table 1). The central section, runs from Carnwath Road Riverside to Chambers Wharf – a length of 12 km. The east section is 6 km long, running between Chambers Wharf and Abbey Mills Pumping Station at the head of the Lee Tunnel. In addition to the primary sections of the main tunnel, the project encompasses the 1 km Frogmore connection tunnel, the 5 km Greenwich connection tunnel and several short connection tunnels.

The project used the NEC3 form of contract (NEC, 2013), and an alliance was also created between Tideway (the employer), Thames Water, the three main works contractors and the system integrator contractor. This collaborative effort aimed to ensure co-operation among

all stakeholders and facilitated knowledge sharing and lessons learned across the four contracts. The three main works contractors were

- joint venture of BAM Nuttall, Morgan Sindall and Balfour Beatty (BMB), responsible for the west section
- joint venture of Ferrovial Construction and Laing O'Rourke (Flo) for the central section
- joint venture of Costain, Vinci Construction Grands Projets and Bachy Soletanche (CVB) for the east section.

Amey was the system integrator contractor, responsible for system-wide process control, communication equipment and software systems for operation, maintenance and reporting throughout the project.

Table 1. Four sections of the main tunnel

| Contract section | Contractor | Main tunnel section | TBM ^a | Drive site | Reception site |
|------------------|------------|---------------------|-------------------|-------------------------|-----------------------------|
| Western | BMB | Main Tunnel A | TBM A (Rachel) | Carnwath Road Riverside | Acton Storm Tanks |
| Central | Flo | Main Tunnel B | TBM B (Millicent) | Kirtling Street | Carnwath Road Riverside |
| Central | Flo | Main Tunnel C | TBM C (Ursula) | Kirtling Street | Chambers Wharf |
| Eastern | CVB | Main Tunnel D | TBM D (Selina) | Chambers Wharf | Abbey Mills Pumping Station |

^aTideway's TBMs were named after women of historical significance in the fields of engineering, science and construction, or with a local connection to their launch site. Nominations came from tideway team members and then a shortlist was put to a public vote (Tideway, 2017)

The main tunnel vertical alignment descends from west to east, beginning at approximately 30 m deep at Acton Storm Tanks and reaching a depth of around 65 m at Abbey Mills Pumping Station. This tunnel was designed with a gradient ranging from 1 in 650 to 1 in 850 for the main tunnels and from 1 in 500 to 1 in 550 for the two long connection tunnels. The tunnel gradients allow gravity-driven flow to Beckton Sewage Treatment Works and also maintain self-cleansing velocities within the tunnel system.

Tunnel construction encountered the entire London Basin geological sequence (Figure 2). In the west section, the tunnel passed through the stiff, over-consolidated clay within the London Clay Formation. The majority of the central section tunnelled through the Lambeth Group, a complex sequence of clays, sands and gravels, which presented more variable ground conditions. Further east, the alignment entered the Thanet Formation where the fine and water-bearing sand required careful groundwater management. The eastern end of the central section and the entire east section passed through the White Chalk Subgroup (from here on referred to as the Chalk). This is a relatively 'soft' material (i.e. possessing a compressive strength typically of 2–5 MPa) containing extensive flint layers as well as numerous bedding and jointing discontinuity fissures and significant fault displacements (Newman and Hadlow, 2021). The contrasting ground conditions across the project necessitated diverse tunnelling techniques and meticulous ground management strategies to maintain face stability and minimise ground movement. To construct the main tunnels and the two long connection tunnels, six tunnel boring machines were employed (TBMs) – four earth pressure balance (EPB) shield TBMs and two

slurry shield TBMs. The short connection tunnels were excavated using sprayed concrete lining (SCL).

The three main works contractors appointed their designers for the permanent works, which included hydraulics, civil/structural engineering, mechanical, electrical and architectural design. The BMB joint venture chose a collaboration of Arup and Atkins (now AtkinsRéalis) alongside Morgan Sindall Engineering Solutions for the western section, while Aecom was the designer for the Flo joint venture in the central section. CVB awarded the permanent works design contract for the east section to Mott MacDonald.

In line with The Construction (Design and Management) Regulations 2015 (HMG, 2015), Tideway appointed Jacobs as the programme manager, who also acted as the Principal Designer, responsible for overseeing health and safety during the design and construction phases. Formerly CH2M HILL, Jacobs managed the employer's reference design, converting requirements into specifications included in the employer's works information, essential for the contract with the main works contractors. The permanent works designers developed a detailed design by adhering to the works information, ensuring compliance with the performance standards established for the project.

The tunnel lining consists of a primary lining and a secondary lining (Figure 3). The main tunnel and long connection tunnels employed a precast steel-fibre-reinforced concrete (SFRC) lining designed to withstand all ground, groundwater and internal and water surcharge loads, with the watertightness of the tunnel ensured by gaskets installed on the precast segments and designed to resist double the hydrostatic pressure. The secondary lining is a

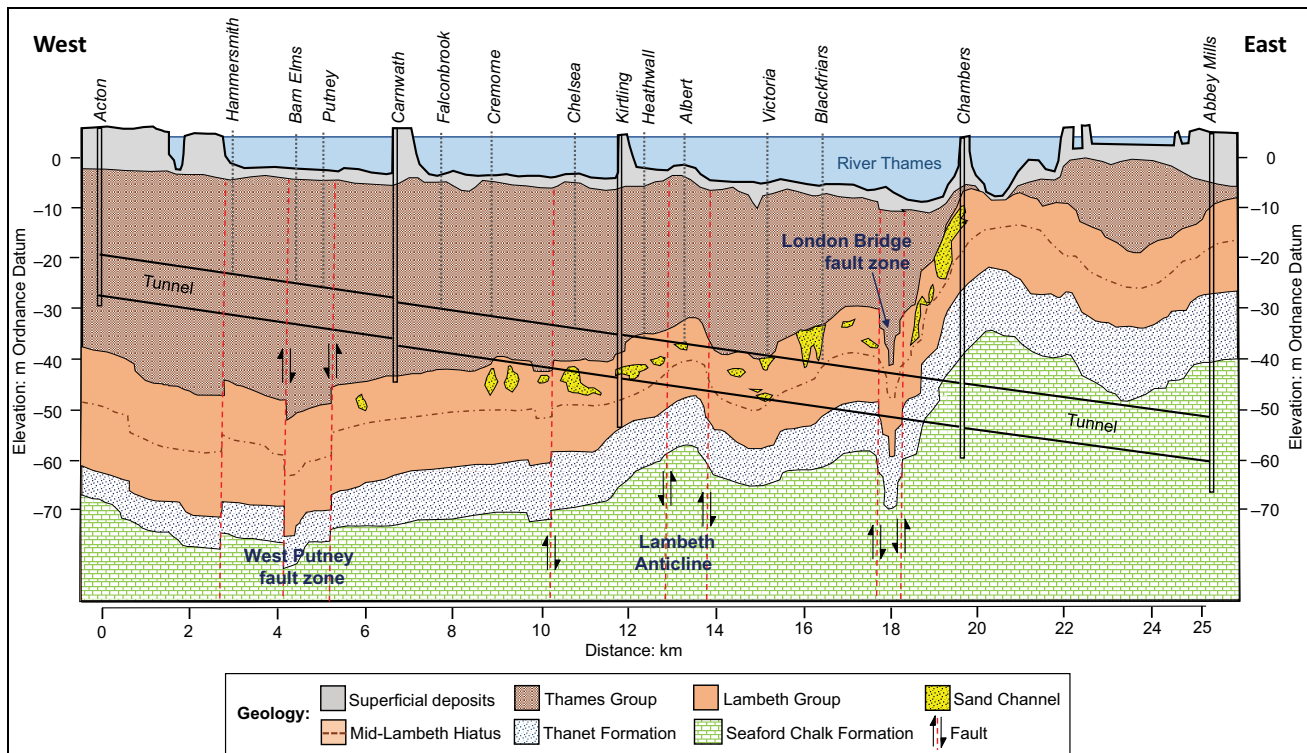


Figure 2. Ground model for the main tunnel (modified from Newman (2022)) indicating the position of significant regional fault structures, the West Putney and London Bridge fault zones and the Lambeth Anticline (Newman and Hadlow, 2021)



Figure 3. Main tunnel primary segmental and secondary cast-in-situ secondary linings

cast-in-situ SFRC lining with steel bar reinforcement at specific locations, such as connection tunnel junctions.

The tunnel lining design was developed to accommodate an internal surcharge pressure, which can arise when the tunnel system is full, resulting in internal pressure that exceeds the surrounding groundwater pressure. It was also designed to handle transient loading, which may occur during rapid filling of the tunnel system. Additionally, the secondary lining acts as a wearing course and protects the primary lining from chemical attack (e.g. from hydrogen sulfide). In areas where a SCL was implemented, it was engineered to either withstand all ground and surcharge loading or share the load with the primary lining. The watertightness requirement was achieved by incorporating a waterproof membrane.

The limits of deviation for all the tunnels were established during the project's Development Consent Order (DCO) (HMG, 2014) application. This defined the maximum allowable variations the contractor could employ when designing and constructing the tunnels. For the main tunnel, horizontal deviation limits were typically set at 5 m each side of the tunnel, while vertical deviation limits were 3 m above the tunnel, with no limit on depth below the tunnel. Despite the allowable vertical deviation, the tunnel had to comply with the vertical alignment requirements to maintain the tunnel gradient.

2. Construction

Construction of the main tunnel was critical to the schedule. To ensure implementation of best practice, the safety of the works and to optimise production, each TBM specification was bespoke for the geology predicted to be encountered, the nuances of drive sites and the preferences of the contractor. The project teams leveraged lessons learned from recent major tunnelling projects and implemented improvements throughout TBM procurement. The focus on TBM optimisation allowed the teams to improve working layouts and enhance safety measures in high-risk areas, including (a) controlled authorised access, (b) facilitating emergency evacuation and rescue provisions, ensuring sufficient redundancy in the TBM refuge and (c) providing physical protection

around hydraulic rams, high-visibility marking of moving TBM components, optimised layout and access for high risk interventions and (d) best practice measures for safe operation and maintenance of spoil removal systems.

A virtual reality model of the first TBM was created for the central section contractor (Flo), allowing a review of all working areas, critical lines of sight, and access and emergency response routes to be interrogated prior to TBM manufacture, facilitating further optimisation ahead of TBM factory acceptance. The virtual model was also used in construction, aiding task-specific briefings, providing familiarisation training and allowing interested stakeholders the chance to understand the tunnel environment and workings of the TBMs while minimising underground visitors.

Further enhancements included axis-level-mounted tunnel conveyor boosters (which reduced installation time and improved maintenance access) and deepening the drive shafts to house conveyor systems, sizers, drive units and high-angle conveyor feeders below temporary working decks – all maximising space at pit bottom considerably – something critical at Kirtling Street where two TBMs were driven simultaneously from a single 32 m dia. shaft (Figure 4).

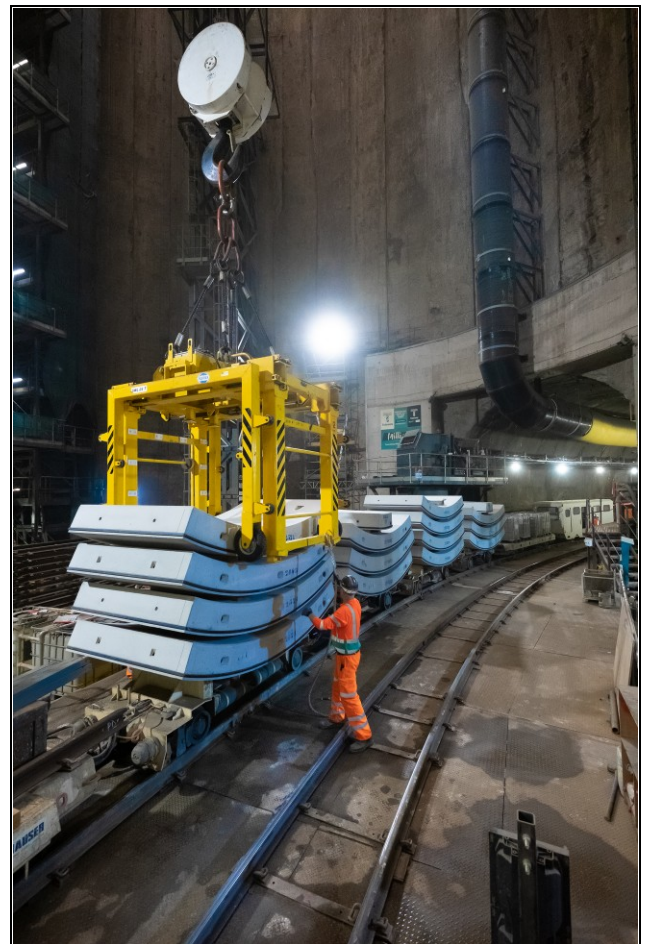


Figure 4. Pit bottom working platform installed above conveyor systems below

The four main tunnel TBMs were launched from three 'on-line' shafts at Carnwath Road Riverside (BMB) and a double-drive site at Kirtling Street (Flo) and at Chambers Wharf (CVB). The depth of the tunnels and the urban-constrained sites necessitated the use of umbilical TBM launches. This involved installing the TBM shield and initial gantries below ground, with backup gantries and systems set up on the surface, connected by umbilical pipes and cables. To support initial launch, critical equipment for the energisation and propulsion of the TBM shields was front loaded, minimising umbilical electrical and hydraulic components as far as practical. Following initial launch using temporary jacking brackets, the remaining gantries were sequentially lowered and connected below ground as the TBM advanced. Once nominal distances were complete, typically 150 m, TBM site acceptance tests were completed.

The primary linings of the main tunnels were precast segmental SFRC components. Where required by design, steel bar reinforced segments were used, typically only during the initial launch phase and at the location of future connection tunnel junctions.

To accommodate the varying geology across the project, the launch and reception shafts of the tunnel drives were broadly aligned to changes in geological formations. This allowed each TBM to be designed for the geology they would encounter.

The EPB TBM used for construction of the eastern tunnel of the central section (TBM C), between Kirtling Street and Chambers Wharf, encountered the most varied geology, launching in a mixed face of London Clay Formation and upper Lambeth Group strata. The TBM progressed through the Lambeth Group and Thanet Formation and ended in full face of Chalk prior to breakthrough at Chambers Wharf (Figure 2). To adapt the TBM for this change in geology and to reduce the likelihood of interventions in areas of highest groundwater pressure and areas of deoxygenated ground gas (both detailed later), a cutterhead intervention for tool reconfiguration was completed below the partially excavated on-line drop shaft at Blackfriars Bridge Foreshore, where a grouted array was installed to tunnel axis level to facilitate safer access for the intervention underground. To effectively manage spoil handling through the changing geology, various conditioning agents were available for use and were implemented based on observed spoil properties and the ability of the conveyor systems to transport arisings.

The main tunnel drive sites were all situated next to the River Thames, with significant enabling works carried out ahead of tunnelling operations. Each drive shaft was enclosed within an acoustic shed, which mitigated noise pollution and improved air quality to nearby receptors. This allowed continuous tunnelling operations, removed weather and seasonal impacts, provided consistent lighting and integrated overhead lifting gantries – all of which optimised safe working conditions and TBM performance, while reducing environmental impacts.

Additional enabling works were implemented to maximise the use of river transport throughout construction. This resulted in 100% of excavated material being exported and all permanent precast segments being delivered to site by river transport (Figure 5). This approach significantly reduced heavy goods vehicle (HGV) journeys, preventing approximately 710 000 HGV movements through London, thus minimising congestion and reducing environmental impact (avoiding approximately 12 100t of carbon dioxide emissions in accordance with UN SDG 13: Climate



Figure 5. Main tunnel segment delivery by barge

action). The TBMs were also delivered by river transport; this allowed far larger components to be delivered, considerably reducing on-site assembly times. More information on this is available elsewhere (Spikesley and Donnelly, 2025).

To enable river transport, the project constructed large cofferdams, temporary jetties, mooring berths, segment handling systems and marine spoil removal systems, the construction and operation of which required significant coordination and agreements with the Port of London Authority, the Marine Management Organisation and the Environment Agency. These facilities, together with large on-site spoil 'muck bays', were carefully planned not only to maximise TBM rates, but also to ensure sufficient contingency during unforeseen river closures, where external factors could restrict river transportation over several tides, severely disrupting tunnelling operations (Figure 6).

While tunnelling works progressed on a continual basis, due to associated fatigue and safety implications of 12 h working shifts,

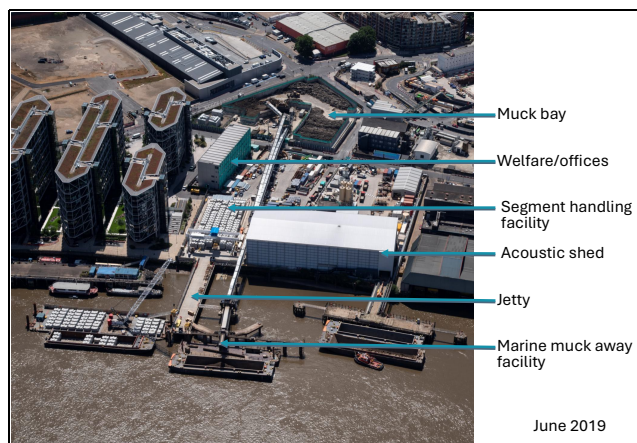


Figure 6. Kirtling Street double-drive site aerial view (photo credit: Patricia Rayner)

Tideway mandated maximum working times of 8 h for below-ground operatives, with up to 10 h permitted dependent on mitigating factors. Each contractor implemented varying shift patterns to comply with this requirement and its implementation is considered to have contributed to the project's excellent health and safety record (Alder *et al.*, 2022).

The construction of the main tunnels was completed between November 2018 and April 2022. TBM tunnelling rates averaged 80–126 m/week across the three contracts. The overall schedule had to contend with unplanned stoppages, including Covid-19 shutdowns that closed drive sites for several weeks (Trigle, 2022). Peak TBM performance was recorded as 272 m/week, with a daily maximum of 54 m achieved by Flo on the eastern tunnel of the central section.

3. Confined space hypoxia

Construction of the main tunnel from Kirtling Street to Chambers Wharf by Flo encountered the most varied geology on the project. A section east of the Blackfriars Bridge Foreshore site, intersected the Upnor Formation at the base of the Lambeth Group. This is potentially 'gassy ground' and a serious hazard for underground works.

Drawdown of the lower aquifer during the industrial growth of London brought air into contact with Lambeth Group sediments on a regional scale. Subsequent post-industrial recovery of the groundwater table trapped and compressed deoxygenated gas beneath overlying impermeable strata (Newman *et al.*, 2013). Historically, hypoxic ground gas was believed to result from the presence of glauconite acting as a reducing agent. However, research conducted as part of the project proved glauconite can remain unoxidised for hundreds to thousands of years under atmospheric conditions (Newman, 2013); the research identified rapid oxidation of 'green rust' (a mixed Fe₂–Fe₃ iron hydroxide) as the most likely cause.

The release of hypoxic gas during tunnelling and underground works is strongly influenced by low or falling atmospheric pressure, typically <1.013 bar (1 bar = 100 kPa) (Newman, 2013; Newman and Ghail, 2020), which adds to the risk of confined space hypoxia. This risk was therefore anticipated and planned for.

Several safety mitigation measures were implemented. First, tunnel ventilation was increased to ensure sufficient dilution of hypoxic gas. Additional in-tunnel monitoring systems were installed, together with the mandated use of portable gas monitoring throughout. The risk to underground construction within the Upnor Formation was highlighted at daily briefings, non-essential visitors were prevented, access permits were revised and standard best practice measures were tightened to ensure the safety of the tunnel environment.

The greatest risk to tunnel operatives in areas of hypoxic ground gas was the confined space entry to the TBM cutterhead during interventions. To reduce this risk, cutterhead maintenance and full tool change was carried out at the Blackfriars Bridge Foreshore site, where hypoxic ground risk was minimal. However, further interventions were required. Although conducted in lower risk areas, to mitigate residual risk, systems of work were revised, mandating the use of masked breathing apparatus for operatives working within the cutterhead chamber. All operatives carried personal gas monitoring systems and local forced ventilation was

increased during all entries. With these measures implemented throughout the Upnor Formation, no trigger levels were breached by the tunnel monitoring systems.

While all mitigation measures proved effective in addressing this anticipated risk, the large diameter of the main tunnel had the most significant impact. Future projects encountering similar ground conditions should thoroughly assess the risk of hypoxic environments and ensure that all supporting systems are appropriately designed to manage it – an aspect that becomes increasingly challenging in tunnels of smaller diameter.

4. Hyperbaric interventions

TBM interventions were carried out periodically to inspect, repair and maintain the cutterheads. This ensured timely replacement of TBM cutting tools (discs, drag bits, scrapers), cleaning of injection ports and proactive maintenance of the cutterhead to maintain optimal TBM performance.

All three main works contractors employed Tony Ridley Hyperbaric Associates (TRHA) – a specialist sub-consultant – thus providing a consistent approach across the tunnelling operations, applying common standards, specifications, training, medicals, operation, supervision and emergency response for hyperbaric works required on all the TBMs.

Work in compressed air, during hyperbaric interventions, is a high-risk highly regulated activity. It poses significant health risks, including decompression sickness (caused by rapid pressure changes), nitrogen narcosis (a narcotic effect of breathing nitrogen under pressure), oxygen toxicity and barotrauma. In the UK, compressed air working is regulated by The Work in Compressed Air Regulations 1996 (HMG, 1996). The standard pressure range for compressed air works in UK tunnelling is between 0 and 3.45 bar. Works above this range are not permitted and require a special dispensation from the Health and Safety Executive (HSE).

Most interventions were carried out under atmospheric conditions. However, on the eastern tunnel of the central section, through water-bearing ground (Lower Lambeth/Upnor Formation and Thanet Formation), the use of compressed air was required to balance groundwater pressure, preventing inundation (Newman *et al.*, 2023). Project ground investigations determined pressures up to 5.1 bar in this section. Consequently, the potential for undertaking work at pressures over 3.45 bar had to be planned for.

The central section contractor Flo and TRHA worked closely with the HSE to gain a permitted exemption from the regulations to enable work outside of the standard pressure range, which necessitated the use of alternative breathing mixtures to air. The process of obtaining the exemption began more than 2 years prior to commencement of tunnelling. Key to this was the need to establish integrated hyperbaric operational and emergency procedures in pressures up to 5.1 bar. The HSE required a pathway of methodology, justification, validation and supporting controls to be established and applied.

Systems included the means for mixed-gas breathing apparatus, required to reduce nitrogen narcosis. All personnel had to undergo rigorous medical screening, specialised training and controlled exposure sessions, all overseen by TRHA and the contract medical advisor (appointed by the HSE). Decompression procedures were carefully planned and monitored, and emergency response systems (including on-site hyperbaric chambers) were established and

maintained to ensure rapid treatment was available, had it been required.

The HSE approval of this project-specific methodology was the first time such mixed-gas training would be delivered for operational use on a UK tunnelling project. The exemption was granted by the HSE in June 2019 and currently remains the only such instance in the UK tunnelling industry.

There was a total of 503 hyperbaric exposures (all on the central section), with interventions carried out between 1.6 and 3.2 bar. Higher pressure interventions took additional time, due to working conditions, reduced exposure limits and increased decompression times. There were 18 individual hyperbaric exposures above 3.45 bar utilising mixed gas, however these were carried out for training purposes to ensure readiness. Fortunately, mixed gas was not required during any intervention.

5. Third-party asset interfaces

The alignment of the main tunnels predominantly follows the River Thames. However, the tunnel deviates landside in the west to Acton Storm Tanks, and in the east under the Limehouse Cut up to Abbey Mills Pumping Station.

The estimated settlement profiles, based on assumed settlement, indicated potential impacts to numerous third-party assets. This necessitated extensive third-party agreements. The project spanned 14 London local authorities and interfaced with over 75 bridge structures, more than 55 tunnels, approximately 1300 buildings, 18 km of existing sewers, 15 km of water mains, 34 km of gas mains and over 20 km of river wall.

Prior to construction, conservative settlement contours were mapped using empirical greenfield settlement predictions with conservative volume-loss values. Surface settlements for the bored tunnels were calculated using the methods outlined by New and O'Reilly (1991), while subsurface movements were assessed using the approaches described by New and Bowers (1994) and Mair *et al.* (1993).

Once the settlement profiles were established, all third-party infrastructure and assets potentially affected by the project were subjected to a three-stage damage assessment process. This began with an initial screening, based on predicted movements, deflection ratios and asset sensitivity. Following this, the asset owners were consulted and assets were progressively assessed to categorise potential construction impacts. Assets that did not pass under-went further sensitivity analysis. Where necessary, additional surveys or mitigation measures were specified. These included enhanced monitoring, detailed assessments (in some cases using finite-element analysis to improve accuracy) and construction mitigation strategies such as defining volume-loss control zones. These zones were implemented in practice through heightened control of the TBMs' operating parameters. Before tunnelling commenced, detailed inspections were carried out to document asset conditions, monitoring equipment was installed and formal agreements were secured with asset owners prior to the TBM entering each asset's zone of influence.

During construction, the key to successful control of ground movement was the ability to identify adverse trends and proactively implement corrective actions. This required knowledge of expected movements, geotechnical properties of the ground, interaction with the construction processes and accurate real-time

monitoring of operating parameters and construction progress. Daily shift review groups set the operating parameters of the TBMs, reviewed monitoring and proactively implemented mitigation prior to trigger levels being reached. Independent review of the tunnelling operation was provided through dedicated control rooms located on the surface at each drive site.

An early challenge arose from the sub-aqueous nature of the main tunnels. With no 'ground level' monitoring possible, measuring the actual ground movement from tunnelling was challenging. Options for riverbed monitoring were explored; however, riverbed scour and sedimentation rendered this impractical for providing timely feedback. For the first TBM launches, an accessible existing service tunnel in relatively good condition was situated in close proximity to the double-drive site at Kirtling Street, allowing continuous monitoring arrays to be installed. The monitoring results from transiting this existing tunnel provided the first as-built settlement contour and volume-loss calculations. These data was crucial in proving TBM performance and confirming the conservative nature of the pre-construction assessments. These data gave asset owners proven data, increasing confidence in the TBM performance, which facilitated a number of third-party agreements with stakeholders.

5.1 Third party interface case study: Tower Bridge

The main tunnel between Kirtling Street and Chambers Wharf passed beneath several tube lines and all central London bridges, including Tower Bridge. Constructed in the late 1800s, Tower Bridge is a Grade I listed steel structure, clad in granite. The main tunnel passed 32 m below the bridge's main pier foundations (Figure 7).

The bridge is owned, maintained and operated by the City of London Corporation (CoLC). Sensors monitored the central gap between the bridge's opening bascules, which showed the bascule gap was temperature dependent, closing considerably during high temperatures. Concerns were raised regarding the ability to open the bridge bascules post-TBM passage. The main concern was not absolute settlement, but a combination of horizontal displacement and rotation of the main towers. This could reduce the bascule gap, which – coupled with warm weather – could jam the bascules, preventing them from opening.

The engineering and construction teams worked closely with the CoLC to inspect and assess the structure. Mitigation measures based on maximum anticipated movements were designed and approved in principle, such that they could have been implemented if required. The plans included physical measures to increase the gap by up to 10 mm following transit, ensuring bridge operation was maintained. Thorough instrumentation and monitoring was installed, including numerous three-dimensional prisms, levelling points, optical displacement sensors, biaxial tilt meters, invar barcodes and distometers (bascule gap monitoring).

All assessments and plans were agreed with the CoLC before permission was granted to transit. Monitoring of the structure was carried out prior to TBM transit, providing a seasonal baseline, and monitoring continued at an increased frequency during TBM passage. To ensure continuous TBM tunnelling beneath the bridge, a hyperbaric cutterhead intervention was conducted 80 m before entering the bridge's zone of influence (ensuring optimal TBM condition) and all tunnel services were extended to reduce any stoppages during transit as far as practical.

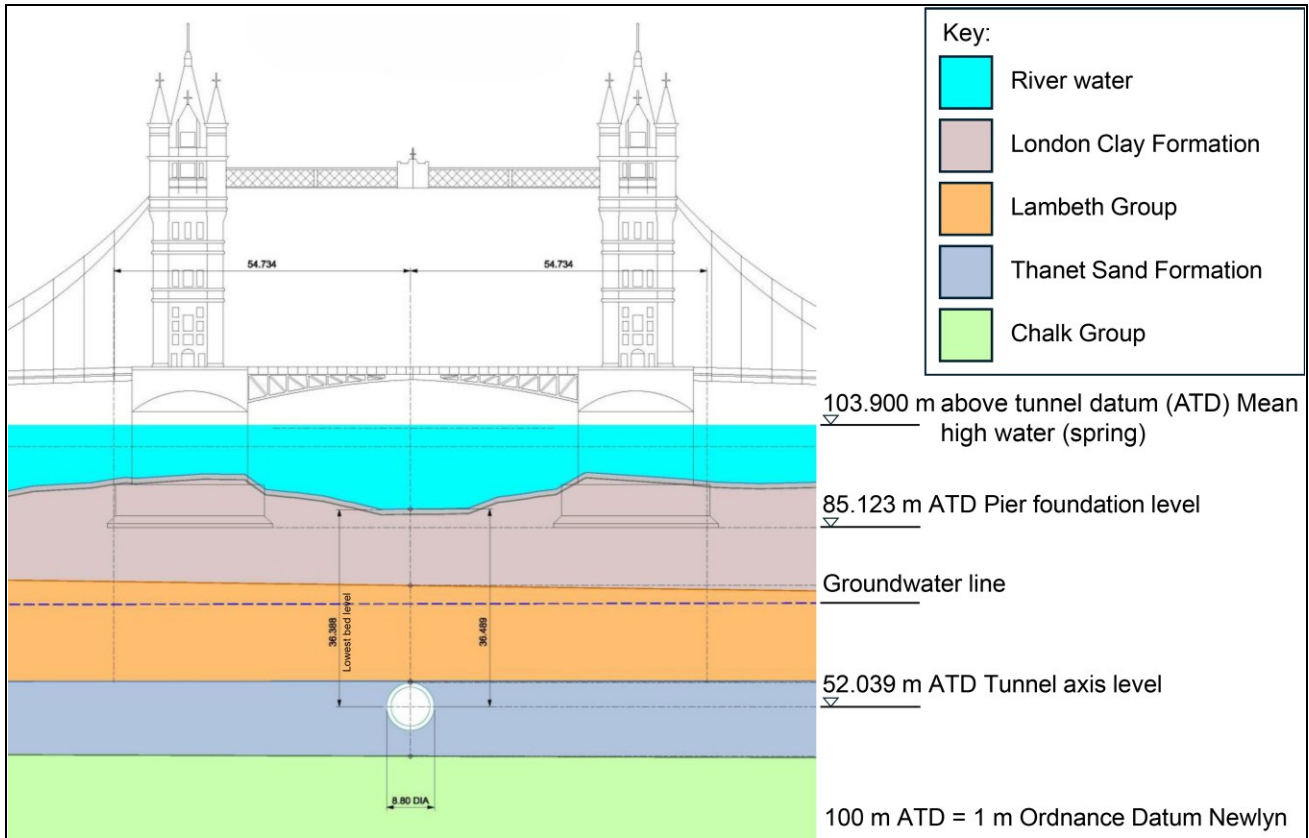


Figure 7. Tower Bridge and relative location of main tunnel

TBM C transited the zone of influence in October 2020, achieving average progress of 24 rings (43 m) per day, with no major stoppages. No trigger levels on TBM parameters, ground movements or structural monitoring were breached. Settlement impacts following TBM transit were deemed negligible, recorded movement was well within the pre-construction estimate and the operation of the bridge was unaffected by the construction of the main tunnel.

5.2 Third party interface case study: Hammersmith Bridge

The western section of the main tunnel, from Carnwath Road Riverside to Acton Storm Tanks, constructed by main works contractor BMB was due to pass Hammersmith Bridge, in early 2020.

Hammersmith Bridge, owned and maintained by the London Borough of Hammersmith and Fulham, is a well-known west London landmark, designed by Sir Joseph Bazalgette. Constructed primarily from wrought and cast iron, with a wooden deck, the bridge's main span is supported by suspension chains secured in concrete anchor blocks.

At the planning stage of the project, the forecast disturbance due to construction of the main tunnel was considered tolerable. However, subsequent routine bridge inspections found the bearing supports to be overstressed, with cracking observed in structural components, primarily due to seized

articulation. As a result, the bridge was closed to vehicular traffic in 2019.

The condition of the bridge was far worse than originally assessed. The original main tunnel alignment only impacted the southern pedestals of the bridge. The greatest concern was differential settlement, as movement would cause additional strain in the suspension chains through settlement of the anchor block, adding to the overstressing of the pedestal.

The DCO defined a limit of deviation of 28.5 m width for this section of the main tunnel (Main Tunnel A). Using this limit of deviation, the alignment of a section of tunnel was amended, up to 10.5 m south (Figure 8). This moved the predicted settlement trough, so that tunnel construction no longer impacted the structural element of Hammersmith Bridge's southern pedestal/anchor block.

With the TBM weeks away, the revised alignment was implemented swiftly. Further checks and agreements were reviewed with the utility companies and third-party assets impacted by the revised alignment. Fortunately, no further damage assessments were required. However, all impacted parties were notified and further pre-construction condition surveys were undertaken.

With the new alignment implemented, the western TBM passed Hammersmith Bridge in March 2020, during the onset of a Covid-19 lockdown (Trigle, 2022). No impact on the bridge structure was recorded.

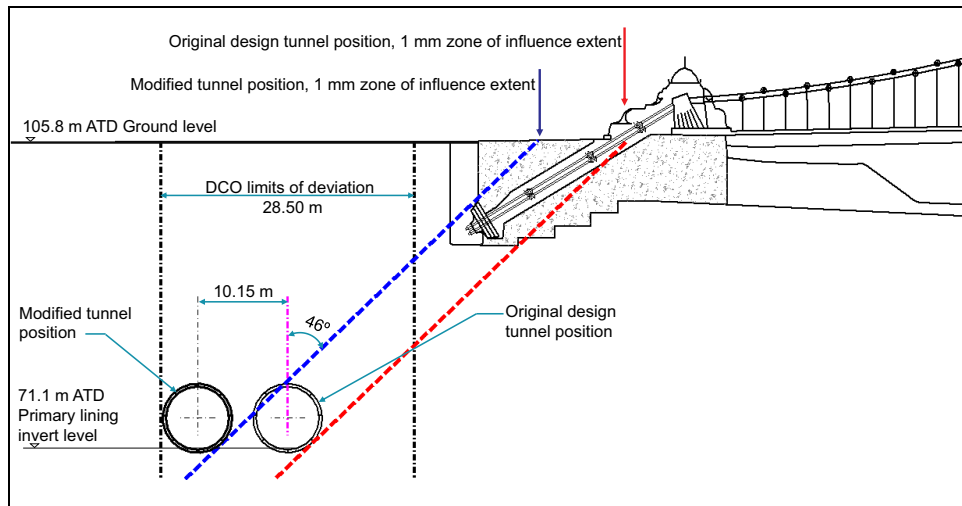


Figure 8. Hammersmith Bridge, main tunnel deviation

6. TBM construction interfaces

The four sections of main tunnel, constructed by three contractors, join at main tunnel drive sites. Managing both the safety and scheduling impacts of these works was fundamental to the delivery of the project, especially given that the TBMs from one contractor were forecast to arrive at the adjacent contractor's active tunnelling site. As such, interface management and the ability to adapt interface arrangements as the project progressed were important tenets of delivery. The two principal inter-contract tunnelling interfaces were between the central westbound TBM B driven to Carnwath Road Riverside and the central eastbound TBM C driven to Chambers Wharf.

6.1 West-central interface

The original intention for the west-central interface was that a TBM reception chamber would be constructed from the Carnwath Road Riverside shaft by BMB, available to receive Flo's TBM B. To support efficient delivery, the reception chamber was initially utilised as a back-shunt to support the logistics required to construct the main tunnel to Acton Storm Tanks, which was being driven from Carnwath Road Riverside (Main Tunnel A). BMB's Main Tunnel A was due to be completed ahead of the arrival of Flo's TBM constructing the tunnel between Carnwath Road Riverside and Kirtling Street (Main Tunnel B), allowing the reception of TBM B and subsequent mobilisation of the shutters required to construct the central secondary lining from Carnwath Road Riverside.

Non-tunnelling challenges associated with the construction of the Carnwath Road Riverside shaft and a change in the launch sequence of the central TBMs resulted in TBM B launching first to provide additional time to obtain dewatering consents for the TBM C tunnelling between Kirtling Street and Chambers Wharf and to prioritise TBM B to cross-under the Thames Water ring main before an agreed embargo period. This resulted in changes to the interface arrangements at Carnwath Road Riverside, as TBM B was forecast to arrive while Main Tunnel A was still

under construction. Detailed coordination between the programme manager, Flo and BMB concluded that the central TBM entering the reception chamber in advance of the completion of Main Tunnel A would cause significant disruption and delay to Main Tunnel A, which was on the critical path for the whole programme. As such, several alternate interface solutions were developed, with three shortlisted

- stop TBM B outside the reception shaft for an extended period (potentially 8 months) and complete TBM B drive upon completion of Main Tunnel A
- 'turn and bury' TBM B, constructing an SCL 'interconnection tunnel' serviced from Carnwath Road Riverside
- turn and bury TBM B, constructing an SCL interconnection tunnel serviced from Kirtling Street.

A comparison of the options was undertaken reviewing factors related to

- health and safety risks
- environmental impacts
- consents and third-party agreements
- cost impacts
- programme impacts.

Conclusion of this review supported turning and burying TBM B off-line, followed by constructing an SCL interconnection tunnel from Carnwath Road Riverside to intersect Main Tunnel B. Selection of the 'turn and bury' option resulted in TBM B diverting north from the originally planned horizontal alignment approximately 90 m to the east of the reception shaft to enable the TBM to stop in its final location. A key element of selecting the final TBM position was ensuring the TBM remained within the limits of deviation as defined within the DCO and minimised impacts on future over-site development.

Prior to agreeing this final position, a review of third-party assets was undertaken, ensuring the selected location minimised the impact of any predicted settlement on assets, including the

Carnwath Road Riverside shaft, river walls, sewers, water mains and existing HV (high-voltage) network.

Working closely with the Environment Agency, it was agreed that a Local Enforcement Position would be granted following suitable assessments to support burial of the TBM. This, alongside an environmental impact assessment, placed requirements on the TBM burial process to ensure that all contaminants were removed from the machine ahead of the backfilling operations.

Upon arrival of the TBM at the burial location, the following stages of decommissioning and backfill were undertaken

- grouting of cutterhead excavation chamber
- grouting of annulus of shield
- secondary grouting of excavation chamber
- grouting of screw conveyor
- stripping TBM of contaminants (oils/greases)
- removing other components of value from the shield (electrical and mechanical items)
- removing gantries (pulled to Kirtling Street and lifted out)
- backfilling of the shield and temporary tunnel, carried out in several sections, with grout delivered from Kirtling Street.

As part of the turn and bury solution BMB constructed an interconnection tunnel from the existing reception chamber at Carnwath Road Riverside (Barrett, 2022), intersecting the segmental lining of Main Tunnel B and in turn connecting the central and west sections of the main tunnel.

The constructed interconnection tunnel is 76 m long with an internal diameter of 8 m, consisting of 350 mm thick SCL. The interconnection tunnel intersected the segmental lining of Main Tunnel B within the backfilled section, enabling the tie-in around the segmental lining to be constructed.

The interconnection tunnel was constructed by driving a 5.4 m internal diameter pilot, installing in-tunnel depressurisation, due to the presence of the intermediate aquifer. The pilot tunnel consisted of 55 inclined full-face 1 m advances with a 250 mm lining thickness. The pilot tunnel was constructed through full-face London Clay Formation before transitioning into a section that contained both the London Clay Formation and an increasing proportion of the segmental tunnel backfilled with cementitious grout. The pilot tunnel was enlarged to a final 8 m internal diameter with the previously installed depressurisation scheme decommissioned as the tunnel progressed.

The primary lining of the interconnection tunnel increased in diameter on the approach to the connection with the segmental lining of Main Tunnel B. Increasing to 10.7 m outer diameter, the SCL interconnection tunnel formed a collar around the segmental lining, providing an overlap of 575 mm. Termed the flare, this element of the interconnection tunnel construction was an important stage in ensuring the integrity of the segmental primary lining as the flare was excavated and sprayed.

The alignment of the interconnection tunnel allowed the tunnel to pass around the shield of the TBM while maintaining an acceptable hydraulic profile, as illustrated in Figure 9.

6.2 Central-eastern interface

The TBM to be used to construct the tunnel from Kirtling Street to Chambers Wharf (TBM C) arrived at the Chambers Wharf shaft while the east team were preparing the launch of the TBM to construct the tunnel from Chambers Wharf to Abbey Mills Pumping Station (TBM D). Two options were reviewed for removal of TBM C. The first option was for the TBM to be dismantled within the reception chamber while tunnelling works between Chambers Wharf and Abbey Mills Pumping Station were undertaken. The concept was to cut up and dismantle TBM C while tunnelling continued, using week-ends to hoist and dispose of the components of the TBM C as TBM D was operating on a five-day working pattern. The second option was to remove TBM C in its entirety once the initial launch of TBM D had been completed. Upon completing a comparative assessment of the options, the decision was taken to remove TBM C in one piece, rather than dismantle in situ. A key challenge in finding the correct solution for the interface at the Chambers Wharf shaft was the interaction between the arrival of TBM C, the launch of TBM D and the additional interface with the Greenwich connection tunnel primary and secondary lining operations.

Upon arrival of TBM C, preparatory works were undertaken in readiness for TBM removal while the initial launch phase of tunnelling between Chambers Wharf and Abbey Mills Pumping Station was completed. Initial works included removing a section of the cutterhead and providing temporary access to ensure adequate arrangements for emergency access and egress and to enable adequate ventilation. The TBM bridge was detached from the gantries, with bogies installed under the screw conveyor to support gantry one, allowing it to be pulled from the tunnel once

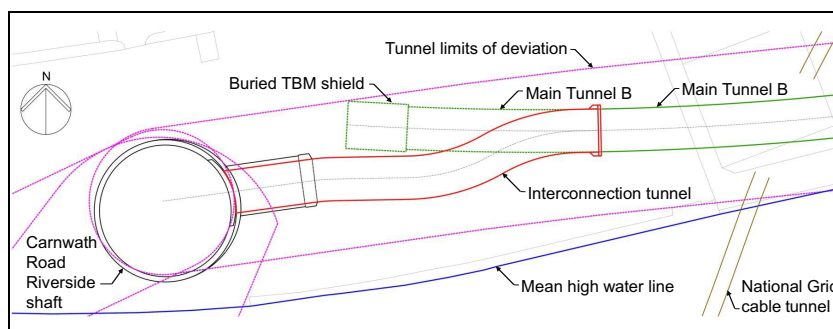


Figure 9. Turn and bury tunnel alignment and location of TBM B shield burial

the shield was removed. Other works completed during the period included separating the backup gantries and placing rails in the reception chamber to support the removal of the TBM shield.

Once the initial launch of TBM D was completed, the Chambers Wharf shaft pit bottom was reconfigured to support the removal of TBM C by a jacking system. Two 50 t jacks were used to pull TBM C from the tunnel to the cradle situated in the pit bottom over a 6 h period (Figure 10). Once in position, the cradle was lifted from the pit bottom to the surface using specialist strand jacks that had been assembled over the shaft (within the noise enclosure) to support removal operations by Mammoet.

Once on the surface, the full TBM shield was removed from site by river. Using a sheerleg barge crane, TBM C was lifted from the cradle and onto a barge for removal from site (Figure 11). The removal of the TBM was meticulously planned



Figure 10. TBM C transitioning from reception chamber to cradle



Figure 11. A 1800 t sheerleg crane lifts TBM C, named Ursula, after cryobiologist Dr Audrey Ursula Smith (© tobyhawkes.co.nz)

as a fixed date was selected to ensure the correct tidal conditions to support the lifting operations. Both the delivery of TBM D and the departure of TBM C by barge highlights the continual use of the river to support construction logistics and reduce the impact on London's roads. Once the main shield and gantries were removed, the pit bottom was reinstated, and main tunnel operations resumed.

7. TBM launch – Greenwich connection tunnel

The Greenwich connection tunnel, constructed entirely within the Chalk, was to be driven from the smaller 18.8 m dia. Greenwich Pumping Station (diaphragm wall) shaft, which was nestled between the Docklands Light Railway (DLR) and existing Thames Water surface and subsurface assets. To facilitate an effective TBM launch, an SCL tunnel was constructed to assemble and launch the TBM below ground. Before excavating the SCL launch tunnel, permeation grouting of bedding and jointing discontinuity fissures within the Chalk was undertaken to minimise water ingress; the water pressure at tunnel level was 4–5 bar. The 17 m long, 8 m dia. SCL launch tunnel was constructed beneath the DLR viaduct, with a 30 m clearance between tunnel crown and the toe of DLR foundation piles (Figure 12). The launch tunnel facilitated the deployment of the TBM for the Greenwich connection tunnel drive to Chambers Wharf.

8. TBM breakthrough – Abbey Mills Pumping Station

Overall, the six TBMs completed tunnelling by breaking through into either a shaft wall or an SCL reception chamber, or were buried in the ground.

The receipt of the slurry TBM used in Main Tunnel D from Chambers Wharf to Abbey Mills Pumping Station required additional provisions within the shaft. The Abbey Mills Pumping

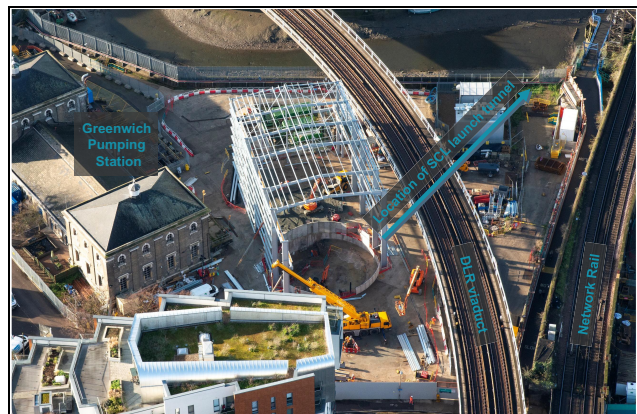


Figure 12. Construction of Greenwich Pumping Station shaft and acoustic shed in close proximity to the DLR viaduct (photo credit: Patricia Rayner)

Station shaft is located near the Prescott Channel, part of the River Lee Navigation, where there is a risk the shaft diaphragm wall would create a path between the upper and lower aquifers, increasing the risk of water entering the shaft during breakthrough and also increasing the risk of ground settlement. To prevent this, it was essential to maintain a full slurry pressure of 4 bar until the shield of TBM D had fully entered the shaft and grouting between the tunnel lining and the shaft lining had been completed.

CVB appointed a specialist designer (OTB Engineering) to design a specialised reception pressure vessel to address these engineering challenges (Figure 13). This vessel, 16 m long, 9.8 m wide and 9.3 m high, was manufactured from modular steel panels for ease of delivery and assembly. The vessel was then backfilled with low-strength concrete to withstand slurry pressures during TBM breakthrough. The Abbey Mills Pumping Station shaft was subsequently filled with water to equalise the pressure of the surrounding groundwater with that inside the shaft. After the TBM completed its drive, the TBM slurry lines were activated to drain the water from the shaft. Subsequently, the pressure vessel was dismantled, the surrounding concrete was cleared and the 950 t TBM D was hoisted out of the shaft (Figure 14).

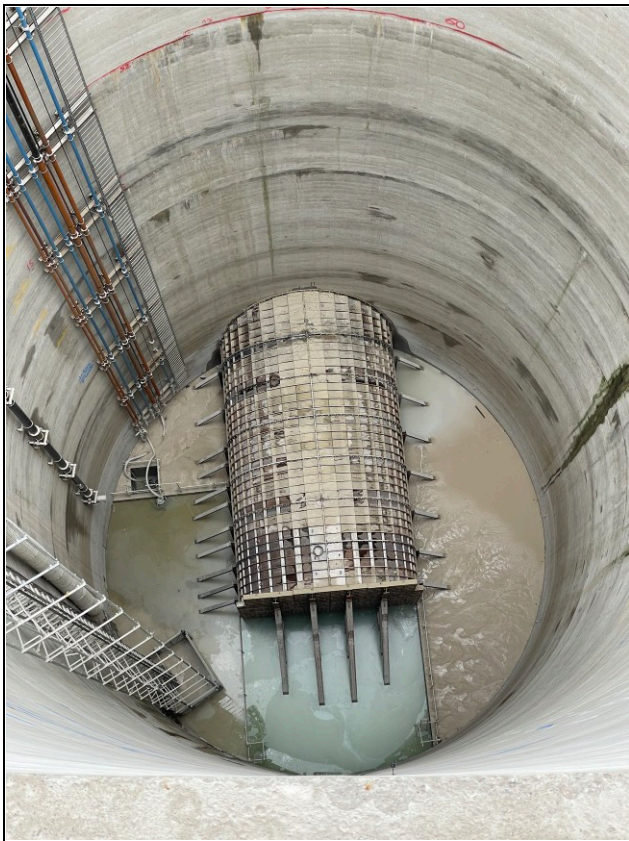


Figure 13. Reception pressure vessel and propping at the base of Abbey Mills Pumping Station shaft

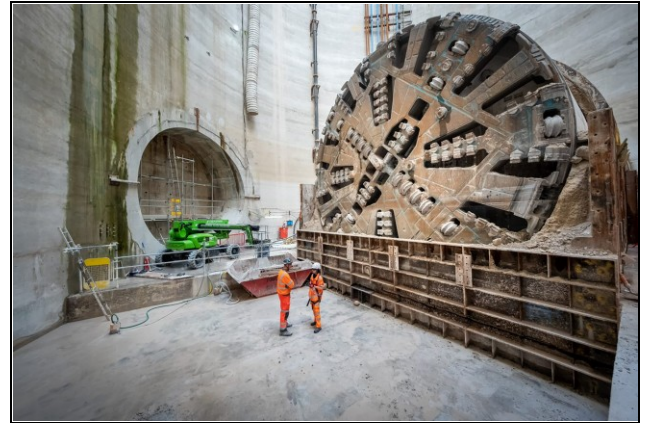


Figure 14. TBM D (named Selina, after pioneering doctor Selina Fox) at Abbey Mills Pumping Station shaft during removal of pressure vessel

9. Conclusions

Completion of the project's tunnels in 2022 marked a major milestone on the critical path to system commissioning, enabling the connection of CSO interception sites and the installation of tunnel secondary linings (Figure 15). The tunnelling works represent a significant achievement, delivering high standards of quality, safety and precision.

Key lessons from this project include the importance of early identification and mitigation of geotechnical risks, such as tunnelling through variable strata, hypoxic ground gas and high-pressure ground conditions. A collaborative contracting model enabled knowledge sharing across the programme, while flexible interface management was critical to the successful management of contract interfaces, as demonstrated through the successful 'turn and bury' solution.

Innovations in health and safety, including reduced underground shift durations, contributed to an excellent safety record, ensuring safer working practices and the wellbeing of all personnel involved. The extensive use of river transport significantly

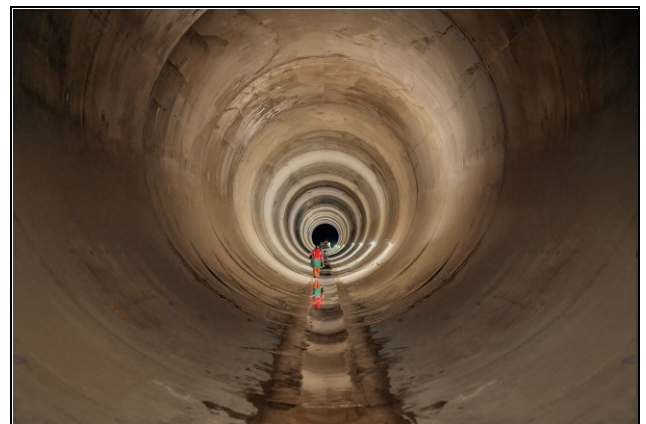


Figure 15. Finished section of main tunnel

reduced HGV movements and carbon dioxide emissions, supporting the project's sustainability and legacy goals.

The unprecedented challenges posed by the Covid-19 pandemic and subsequent lockdowns were met with resilience and adaptability, with the project progressing without significant delay.

Despite the challenges faced, the project team demonstrated exceptional coordination and problem solving, ensuring best-for-project integration to deliver the main component of the super sewer that will serve London for the next 120 years and beyond.

Moreover, the successful completion of the tunnelling works without impacting third-party assets underscores the meticulous

planning and execution that defined the project. The Thames Tideway Tunnel stands as a testament to engineering excellence and collaborative effort, paving the way for a cleaner, more sustainable future for London.

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