The Lee Tunnel Shafts

London's largest and deepest ever shafts for the scheme to eliminate sewage discharges to the River Lee

by Peter Jewell MA MSc DIC CEng MICE and Mark O'Connor BSc CEng MIStructE

The Thames Water Lee Tunnel is the first stage of improvements to London's sewer system which will remove combined discharges of storm water and sewage to the River Thames and lower River Lee. The tunnel, which will have an internal diameter of 7.2m, is being constructed at an average of 75m below the ground, running 6.9km from the Abbey Mills Pumping Station complex to the Beckton STW in East London. The tunnel is required to store 350,000m^3 of stormwater and sewage, which is pumped out to Beckton STW following each tunnel filling event. The project requires the formation of four shafts, and this article details this part of the project.

Slipforming Beckton Overflow Shaft lining wall - Courtesy of Thames Water

Background

At the Abbey Mills Pumping Station in Stratford, East London, a single Combined Sewer Overflow is responsible for about 40% of all stormwater flows into the River Thames. The Lee Tunnel will carry these stormwater flows from Abbey Mills to Beckton STW, which is being upgraded and expanded to ensure that the facility can handle these additional loads.

The Lee Tunnel is part of Thames Water's London Tideway Improvements Scheme, which will return the River Thames to an acceptable state of cleanliness by 2020.

Figure 1 (see next page) illustrates the key components of the Lee Tunnel system. Eventually a further tunnel, which will capture the discharges to the River Thames upstream of the River Lee, will be connected to the Lee Tunnel at Abbey Mills.

Undertakings

MVB, a joint venture of Morgan Sindall, Vinci Construction Grands Projets and Bachy Soletanche, were awarded a design and construct contract for the Lee Tunnel in early 2010, with UnPS, Bachy Soletanche and Mott MacDonald acting as the detailed designers. The £635m project is being delivered under a NEC 3 Option C form of contract. Thames Water's Project Management Team, led by CH2M Hill and including AECOM, work at site in a collaborative 'one team' manner with MVB. Prior to contract award AECOM had undertaken the concept, planning, and reference design for the Lee Tunnel on behalf of Thames Water.

The Lee Tunnel shafts

The four permanent large diameter shafts, three sited at Beckton STW and the fourth at Abbey Mills, are some of the largest ever constructed in the UK. They are sized and function as follows:

Partnership brings success

Morgan Sindall, VINCI Construction Grands Projets and Bachy Soletanche are working together as MVB, combining world-class expertise, together with CH2M Hill, to deliver the Lee Tunnel for Thames Water. An essential step in providing the capital with a 21st century sewerage system.

www.mvbjv.co.uk

- ***Beckton Overflow Shaft:***
  20m internal diameter, 74.5m to invert level.
  This shaft serves as the TBM launch shaft during construction, and upon completion will connect to a new outfall to the River Thames.
- ***Beckton Connection Shaft:***
  25m internal diameter, 78.5m to invert level.
  This shaft is sited directly on the line of the main tunnel, and will transfer tunnel sewage flows to the Pumping Station shaft via a separate interconnecting suction tunnel.
- ***Beckton Pumping Station Shaft:***
  38m internal diameter, 86.5m to invert level.
  The Pumping Station Shaft is a dry shaft housing up to 6 (No.) 3.05MW pumps, which will transfer the tunnel sewage flows up to the treatment works at Beckton.
- ***Abbey Mills Connection Shaft:***
  25m internal diameter, 68.0m to invert level.
  This shaft is at the upstream end of the Lee Tunnel and will serve to receive the TBM from the main tunnel drive. Upon completion, this shaft will transfer sewage flows from two pumping stations at Abbey Mills into the main tunnel.

All the shafts have been designed to Eurocodes and are required to meet specific water tightness criteria, as set out in the contract specification, to resist both external groundwater pressure and internal sewage pressure.

Each shaft contains internal and ancillary structures specific to their operation within the overall scheme. These structures are not described in this article.

Diaphragm walls

The primary walls of the four shafts are constructed of reinforced concrete diaphragm wall panels. Their design had to consider an assessment of ground stiffness including for chalk, high hoop stresses, large multiple openings and non-axisymmetric loadings. These considerations led to the diaphragm wall shafts being formed of overlapping rectangular panels up to 1.8m wide and 98m deep, which needed to accommodate:

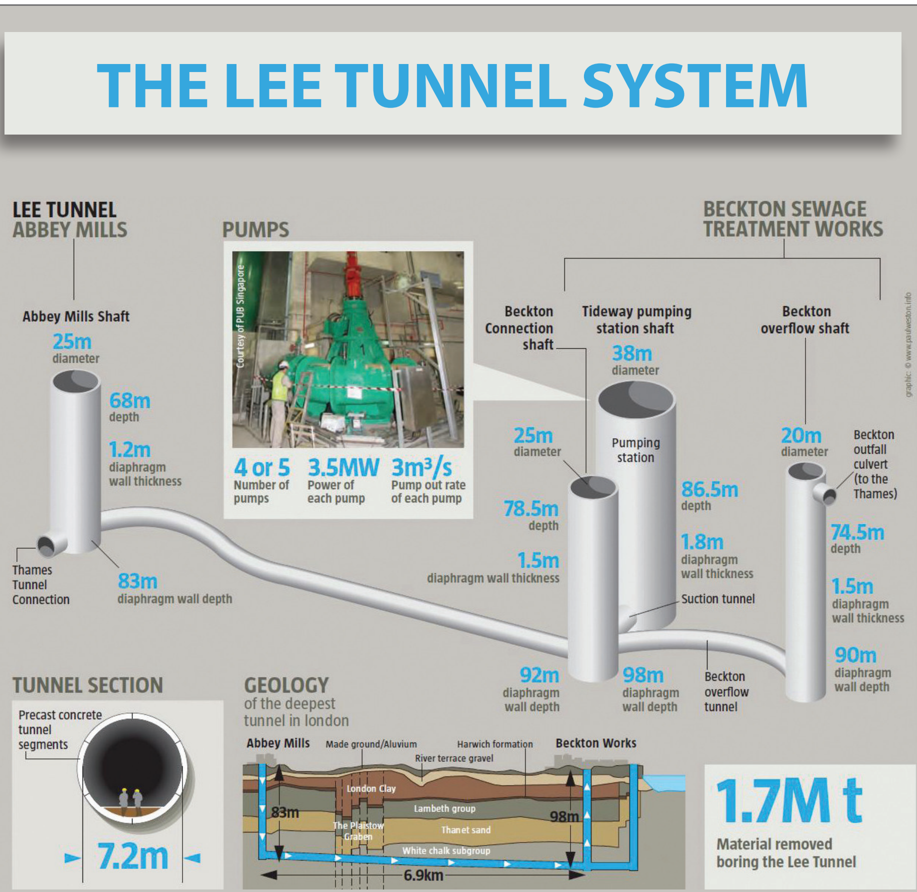
- Bespoke design of concrete mix.
- Verticality tolerances of 1 in 300.
- Design and safe accurate placement of reinforcement cages full depth.
- Management of bentonite support fluid.
- Verification of the as-built design.

It is clear from the two shafts that have now been fully excavated (the Beckton Overflow and Connection Shafts) that the required verticality of the diaphragm walls has been achieved, and correlates with the survey information obtained during installation.

The diaphragm wall panels form a faceted circle, with primary panels excavated up to 7.2m long with overlapping secondary panels cutting into the concrete of the primaries.

The primary panels were constructed at a rate of one per week, with panel sequencing coordinated such that excavation could continue at a safe distance from cage placement and concreting. Excavation of the primary panels was sequenced such that concrete of similar strength existed on each side of a secondary panel.

The diaphragm walls were excavated by means of conventional grabs in the upper superficial deposits, and by a *Hydrofraise* rig through the underlying Lambeth Group, Harwich Formation, Thanet Sands and Chalk. The excavations utilised bentonite fluid throughout, which acts both as a support fluid and as a medium to pump the excavated cuttings back to the surface.



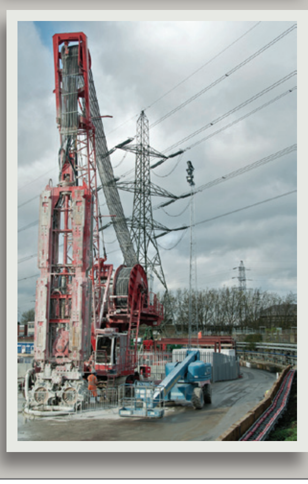


Figure 1: The Lee Tunnel System - Courtesy of Thames Water

Diaphragm wall construction involved large concrete pours (up to 1,400m^3 in an individual panel), which required the concrete mix to maintain sufficient workability throughout to ensure the pour could be completed without the concrete setting too quickly.

A concrete mix grade C50/60, incorporating 70% ground granulated blastfurnace slag (GGBS) cement replacement, was used for the diaphragm walls. The high workability requirement enabled placement via tremie pipes, ensuring a good degree of self compaction was achieved throughout the pour, particularly at base slab level where the highest density of reinforcement is located.

In order to avoid the formation of 'cold' construction joints during these very long concrete pours, the concrete mix was designed for workability retention of 6 hours. The GGBS in the concrete mix reduced the early temperature gain and the rate of strength gain, with the intention that the minimum compressive strength of 60MPa would not be achieved until 56 days. This enabled the subsequently constructed adjacent secondary and infill panels to 'bite' into primary panels, thus ensuring an 'overlap' detail.

In the vicinity of the tunnel openings in the Beckton Overflow and Connection Shafts, 'soft' eyes were created by replacing the steel reinforcement with glass fibre reinforcing bars, in order to facilitate easier 'break outs'/'break ins' for the TBM during tunnelling.

Shaft lining walls

The new design guidance from Eurocodes for water-resisting design restricts concrete crack widths further than was previously allowed for design to BS8007. To comply with Eurocode, a greater volume of reinforcement would thus be required within the lining. A dense matrix of reinforcing steel would be difficult to detail and install, and inhibit the placement of well-compacted concrete. This led to a major design change.

A radical design of the shaft lining walls as 'plain' concrete walls has helped to eliminate the majority of the reinforcing steel from within each shaft wall. Believed to be a world-first, pressure from a concrete pour behind the shaft linings is being used to create and maintain hoop compression, counteracting hydrostatic pressure from within.

Behaviour of the walls during construction and long-term operation influenced the development of the structural solution. For the majority of the time the three 'wet' shafts will be empty, but after heavy rainfall they may fill to the top with combined stormwater run-off and sewage. At the base of the shafts, up to 8 bars of internal hydrostatic pressure, counterbalanced partly by the external groundwater pressure, will have to be resisted.

Circular concrete structures work optimally in hoop compression. Therefore if tensile stresses are prevented from developing within the shaft lining, by maintaining it permanently in compression via structural continuity between the lining wall, diaphragm wall and the surrounding ground, the need for reinforcement can be removed altogether. This will also prevent the formation of tensile cracking within the concrete.

MVB chose to adopt a double sided slipform shutter to construct the 700-750mm thick lining wall and thus formed a free standing concrete cylinder within the excavated shaft. The slipforming construction permitted the cylinder to contract vertically and horizontally without restraint. The design requirement for the inner lining wall to contract and be able to move laterally under pressure was achieved via the installation of a slip joint at base slab level.

The inner lining wall was constructed using a steel fibre reinforced concrete grade C50/60 incorporating 36% GGBS cement replacement. The mix was designed to accommodate continuous

Two Hydrofraises working at Beckton Pumping Station and Connection Shafts - Courtesy of Thames Water


Diaphragm wall reinforcement cage
Courtesy of Thames Water


Excavating the Beckton Connection Shaft
Courtesy of Thames Water


Fixing prefabricated base slab reinforcement
Courtesy of Thames Water


Full scale slipform trials
Courtesy of Thames Water

slipforming and thus avoid the formation of 'cold' construction joints, which would have a detrimental effect on the future water tightness of the lining wall. A plasticiser and retarder were incorporated within the mix, with the level of retardation being monitored, and adjusted as necessary to suit the planned pour rates and formwork travel speeds achieved. The workability of the concrete was critical in allowing the formwork to travel upwards continuously, as well as enabling the surface finish to be worked upon from the trailing platform of the slipform rig.

The slipform process for the Beckton Overflow Shaft progressed well achieving the required quality of finish, and provided confidence that construction of the other shafts will be equally successful.

Designing the lining walls as plain concrete with minimal reinforcement assisted the slipform process. Steel fibres incorporated within the mix increase the ductility of the unreinforced concrete, eliminate spalling damage, and assists in controlling drying shrinkage cracking.

Construction of the lining wall created an annulus between the lining and diaphragm walls. The annulus is backfilled with a grade C25/30 concrete incorporating 50% GGBS cement replacement in a continuous pouring operation using a retardant and a plasticiser to keep the concrete fluid for at least 12 hours, enabling it to flow evenly around the shaft perimeter and self compact. A head of fluid concrete is able to build up exerting pressure onto the lining wall, before the lowest levels began to set, locking in a compressive force within the lining wall. The early pressurisation puts the concrete into compression, further minimising the risk of shrinkage cracking. Instrumentation placed in the annulus has enabled concrete temperatures and pressures to be monitored in real time, in order to confirm design assumptions.

During pressurisation via the annulus concrete, the lining contracts and moves inwards. At the base level, the lining wall sits on the slip joint comprising 2 (No.) layers of 2mm thick PVC slip membrane with grease in between. The 'slip membrane' arrangement was verified by laboratory testing under an applied compressive stress to represent the inner lining wall load. The slip joint enables the lining wall to move with minimal restraint, and thus prevent any stress build-up from induced bending that would otherwise cause cracking and inhibit the pre-stress.

The construction of the internal structures within each shaft are sequenced to follow on after contraction of the lining wall has occurred, or else to accommodate a soft joint where they abut the lining wall.

Base slab

Applying the same 'first principles' design approach, an inverted dome solution was developed for the base slab. Uplift pressure on the base slab places the dome under compression and creates an arching action, substantially limiting bending and shear effects. Outward thrust is resisted by constructing the base slab contiguous with the diaphragm wall – effectively transferring the force directly into the surrounding chalk. This approach enabled a significant reduction in the tonnage of steel reinforcement required.

MVB engaged a French steel fixing subcontractor, SAMT, specialising in the detailing, bending and fixing of reinforcement to be involved in the development of the detailed design. SAMT's review enabled a prefabricated radial cage solution to be adopted in order to reduce the number of operatives within the shaft and shorten the critical path on the construction programme.

The base slabs are constructed using concrete grade C40/50 incorporating 55% pulverised fuel ash (PFA) cement replacement, as well as a retarder and a plasticiser. High workability is required for the base slab mix to enable the concrete to be pumped from the surface, as well as to aid good compaction during pouring of the domed section of the slab, where the majority of the reinforcement is located. As the base slabs are over 4.0m thick in the centre, a primary design requirement for the concrete mix was to reduce the heat of hydration, and thus minimise early age temperature gain during curing to prevent cracks forming, which was achieved via the use of PFA. The top surfaces of the slabs cast to date have achieved a good finish with no cracking present.

The design addressed the elimination of water paths at construction joints by the installation of the Drytech system of re-injectable channels.

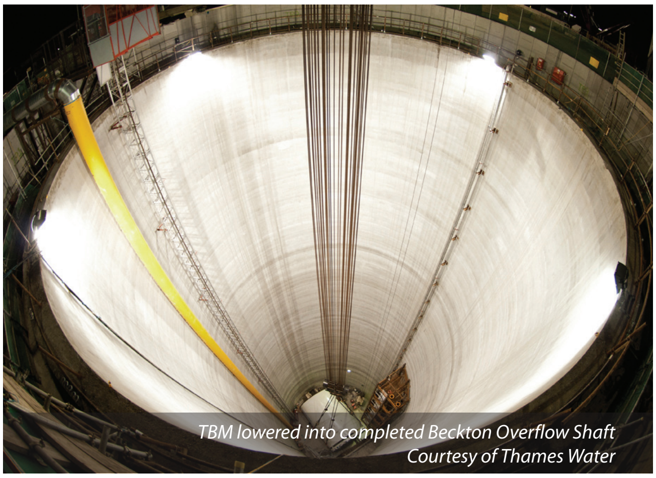
Conclusions

An innovative design approach to the shaft linings of the Lee Tunnel, together with careful design detailing for the base slab and the specification of the concrete used for the various components, represents a unique and radical approach which has proved to be successful.

Not only have these design innovations yielded a significant commercial saving on steel, but by largely removing the need to handle and fix heavy reinforcement, they have enabled faster, safer construction. Over the lifetime of the Lee Tunnel, minimising the steel content significantly improves durability. The major concerns of steel corrosion and spalling common to all reinforced concrete water-retaining structures, but particularly those subjected to the aggressive compounds found in sewage, are much reduced.

The Editor & Publishers thank Peter Jewell, Engineering Manager, of CH2M Hill and Mark O'Connor, Principal Engineer, of AECOM, for preparing the above article. The authors and Publishers thank Thames Water for permitting the publication and presentation of this paper.

Slipforming Completed at Beckton Overflow Shaft
Courtesy of Thames Water



TBM lowered into completed Beckton Overflow Shaft
Courtesy of Thames Water