Design and Construction of Permanent Steel Fibre Reinforced Sprayed Concrete Lining Shafts for the Thames Tideway Tunnel Project UK

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ABSTRACT: The West Contract of Thames Tideway Tunnel involves the construction of 7No deep shafts, one 7km Main Tunnel and 4No. connecting Tunnels through London Strata. Of particular interest are the Shafts, which are designed as composite linings with Steel Fibre Reinforced (SFR) Sprayed Concrete Lining (SCL) as Primary Lining and Cast In Place (CIP) SFR Concrete as Secondary Lining. Emphasis is given to the design and construction of the largest SCL shaft of the West contract (also the largest SCL Shaft constructed in the UK in terms of depth and diameter), at Carnwath Road Riverside (up to 25m ID, 50m in depth), from which the Launching of the Tunnel Boring Machine (TBM) will occur. The design philosophy required the development of a special SFR SCL mix with enhanced water resisting capacity to enable the omission of waterproofing membrane from the works. This Paper discusses the design philosophy, the extensive SCL trials, the construction challenges and the monitoring results thus far.

1 INTRODUCTION

1.1 General

The quality and performance of critical city infrastructure, such as Thames Tideway Tunnel is essential for supporting economic growth and productivity in a city, such as London, in the 21st century. The construction of the new ‘super’ sewer aims to enhance city infrastructure and make it resilient to changing patterns. It also needs to be constructed efficiently in terms of cost, low carbon footprint and service performance.

The West Contract of Thames Tideway Tunnel includes the 6.5m ID, 7km long Main Tunnel alignment and a number of associated structures between Acton Storm Tanks and Carnwath Road River side (CARRR) worksites. This also includes the Frognmore Connection Tunnel that links the King Georges Park and Dormay Street worksites to the Main Tunnel. The Main Works Contractor, BAM Nuttall-Morgan Sindall-Balfour Beatty (BMB) Joint Venture, has appointed Morgan Sindall Engineering Solutions Limited (MSES) for the design of the Tunnels and Shafts structures. The majority of the shafts feature double linings, a Primary Steel Fibre Reinforced (SFR) Sprayed Concrete Lining (SCL) and a Secondary Cast In Place (CIP) Steel Fibre Reinforced (SFR)/Steel Bar Reinforced Concrete (RC) Lining.

<table>
<thead>
<tr>
<th>Shaft</th>
<th>Internal Diameter (m)</th>
<th>Excavation Depth (m)</th>
<th>Primary Lining Thickness (mm)</th>
<th>Secondary Lining Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carnwath Road Riverside</td>
<td>25</td>
<td>49.5</td>
<td>SCL: 575 to 1050</td>
<td>SFR/RC: 600</td>
</tr>
<tr>
<td>Hammersmith Pumping Station</td>
<td>11</td>
<td>35.5</td>
<td>SCL: 425</td>
<td>SFR/RC: 325</td>
</tr>
<tr>
<td>Barn Elms</td>
<td>6</td>
<td>36.0</td>
<td>SCL: 325</td>
<td>SFR/RC: 250</td>
</tr>
<tr>
<td>Acton Storm Tanks</td>
<td>15</td>
<td>35.7</td>
<td>SCL: 400</td>
<td>SFR/RC: 400</td>
</tr>
<tr>
<td>Dormay Street</td>
<td>12</td>
<td>26.5</td>
<td>SCL: 325 to 750</td>
<td>SFR/RC: 300</td>
</tr>
<tr>
<td>King Georges Park</td>
<td>9</td>
<td>23.3</td>
<td>SCL: 325</td>
<td>SFR/RC: 500</td>
</tr>
<tr>
<td>Putney Embankment Foreshore</td>
<td>6</td>
<td>38.3</td>
<td>RC (caisson): 725</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. West Contract of Thames Tideway Tunnel Shafts – general information
This Paper focuses on the Shaft Lining design philosophy and construction aspects of the largest Shaft (CARRR) in the West Contract of Thames Tideway Tunnel, which is also the largest shaft (in terms of depths and diameter) constructed in the UK in ‘soft’ ground using SCL techniques. The CARRR shaft (as per all shafts) includes internal Vortex structures, high level platforms and other features to facilitate their hydraulic function. A Building Information Modelling (BIM) model has been created to enable effective design delivery, updated construction information and provides a framework for efficient asset management and maintenance.

Figure 1. A detailed BIM model was created including all permanent works elements.

1.2 Carnwath Road Riverside

The Carnwath Road Riverside worksite site is located adjacent to the tidal River Thames in the London Borough of Hammersmith and Fulham. The shaft located here is the tunnel drive and reception shaft for the main alignment tunnel and shall receive flow from the main tunnel as well as from the Frogmore Connection Tunnel.

1.3 Ground and groundwater conditions

Ground conditions are typical of the London Basin with made ground and soft deposits overlain the medium dense Terrace Gravel and London Clay Formation, in which the majority of the shaft excavation took place. The shaft base slab construction is in the variable Lambeth Group (LMB), which is characterized by mixed ground conditions.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Top Level (mATD)</th>
<th>Groundwater (kPa)</th>
<th>Soil Shear Strength (phi)</th>
<th>Soil Stiffness (MPa)</th>
<th>Permeability (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made Ground</td>
<td>105.5</td>
<td>0</td>
<td>30</td>
<td>10</td>
<td>0.864</td>
</tr>
<tr>
<td>Alluvium</td>
<td>102.0</td>
<td>5</td>
<td>25</td>
<td>5</td>
<td>0.864</td>
</tr>
<tr>
<td>Terrace Gravel</td>
<td>101.0</td>
<td>10</td>
<td>35</td>
<td>35</td>
<td>8.64</td>
</tr>
<tr>
<td>London Clay</td>
<td>94.5</td>
<td>25</td>
<td>25</td>
<td>72</td>
<td>8.64 x 10^6</td>
</tr>
<tr>
<td>Harwich</td>
<td>59.5</td>
<td>320</td>
<td>27</td>
<td>72</td>
<td>0.864 x 10^3</td>
</tr>
<tr>
<td>USB/UMB</td>
<td>59.0</td>
<td>380</td>
<td>27</td>
<td>80</td>
<td>0.864 x 10^3</td>
</tr>
<tr>
<td>LMB Silt</td>
<td>52.5</td>
<td>445</td>
<td>35</td>
<td>80</td>
<td>8.64 x 10^3</td>
</tr>
<tr>
<td>LMB clay</td>
<td>49.0</td>
<td>480</td>
<td>27</td>
<td>80</td>
<td>0.864 x 10^3</td>
</tr>
<tr>
<td>Upnor</td>
<td>45.0</td>
<td>410</td>
<td>40</td>
<td>80</td>
<td>0.363</td>
</tr>
<tr>
<td>Thanet Sand</td>
<td>39.0</td>
<td>460</td>
<td>40</td>
<td>200</td>
<td>0.950</td>
</tr>
</tbody>
</table>

Table 2. CARRR Geological and Groundwater Conditions
Thanet Sand is underlain by the Chalk formation at +32metres Above Tunnel Datum (mATD). There are three distinct aquifers; Upper (Terrace Gravels), Medium (London Clay and Upper Lambeth Group) and Lower (Upnor, Thanet Sand and Chalk). See Figure 6 for a geological long-section.

2 DESIGN

2.1 Design Philosophy

The design philosophy for the SCL tunnels and shafts encompasses all the necessary provisions to satisfy the Works Information requirements and also minimises construction, operation, maintenance and decommissioning Health and Safety risks. In order to fulfil the above all lining works are designed in accordance with the principle that the Primary and the Secondary Lining work compositely.

The Primary Lining is installed taking the initial ground and water loading, therefore ensuring the Secondary Lining installation is carried out stress-free. The inevitable additional external pressure resulting from clay consolidation, variations in the underground water, seepage, surcharge changes, creep etc., lead to the development of an additional hoop force. Under this load, the Primary Lining deforms and activates the Secondary Lining, resulting in the two linings working together in a combined manner. The two linings are bonded with friction, adhesion and interlocking at the concrete interface. See figure 2 below:

Construction Phase 1: Only Primary Lining installed – initial loading;

Construction Phase 2 (design case): Primary and Secondary (installed stress-free) acting in a ‘Combined’ behavior;

Operation (surge): Primary Lining in compression, Secondary Lining in tension;

Figure 2. The composite behaviour of the lining in the temporary and permanent condition.
2.2 Performance requirements

The Works Information specifies the performance requirements which form the key criteria for the SCL and can be summarized as follows:

1. Design Life 120 years
2. Limited water ingress/egress (damp patches no running water), on average 0.1 l/m²/day ingress permitted
3. Design for a maximum internal grade line of 104mATD.

2.3 Design Analysis

2.3.1 Design cases

During operation, the shafts will be filled with sewage at regular intervals and then emptied, according to the operational requirements. Consequently, based on the above description, two principal Design Cases determine the design limit states for the shaft:

SHAFT EMPTY: Highest external groundwater level with no internal pressure. The external ground water and earth pressures oppose the internal pressure, and therefore the worst loading case is when the shaft is empty. This state of stress represents the worst load condition for the primary lining and the portal structures, the maximum bending moments and stresses are anticipated to develop in the structure, which govern the shaft design. The ground water level is taken as the maximum level.

SURGE CONDITION: Lowest characteristic external groundwater level, highest internal water level (104mATD). That means the internal pressure at base slab level will be a 45m head. The design has been facilitated by the use of Non-linear Finite Element (FE) analysis. To that end PLAXIS 2D and Strand7 have been used in 2D and 3D analyses respectively.

Design of SCL has been carried out considering limited relaxation in soft ground resulting in early loading of the lining. Therefore, the SCL will provide early age support of the ground, minimising the settlement and optimising safety. Furthermore, critical intermediate stages of construction are modelled and their structural stability is checked.

For the STR/GEO Ultimate Limit State verification of the shaft, the BS EN 1997-1:2004 Design Approach 1 has been adopted in line with UK National Annex. Two calculations (Combination 1 for STR limit state and Combination 2 for GEO limit state) are hence performed for both the empty shaft and the surge design conditions. Within the context of the FE design analysis, the partial factors in Combination 1 are applied to the effects of actions (forces/bending moments are multiplied by a partial factor – greater than 1.0 - to yield design values). It is however difficult to apply Combination 2 within the framework of FE design analysis, as factoring the soil strength often results in the soil exhibiting unrealistic yielding behaviour. Therefore, Combination 2 is used to explore the sensitivity of the structure to extreme situations such as low soil softening and seepage analysis through the shaft lining. In these cases, the partial factors for actions in Combination 2 are applied directly to material properties and actions. For the excavation stability, the excavation stages were checked carrying out a C-Phi reduction analysis and couple stress-flow analysis using PLAXIS (FE modelling).

Lining thicknesses were verified for Ultimate and Serviceability conditions according to BS EN 1992-1-1:2004+A1:2014 and where SFR Concrete elements were included according to fib Model Code 2010 (fib, 2013).

2.3.2 Shaft Watertightness

The Primary Lining and Secondary Lining will work in a combined manner in order to provide the necessary watertightness. The Primary Lining will operate in full hoop compression and hence no tension is expected to develop within it, whilst the Secondary Lining is partially in tension under surge conditions. The required degree of watertightness will be achieved by adopting a combination of measures, including the combined action of Primary and Secondary Lining. The ‘Primary’ measures include the Primary SCL acting compositely with the CIP Secondary Lining along with selection of a suitable concrete mix. The concrete mixes specified ensure the structural elements are of sufficiently low permeability, which include the use of high performance steel fibres to control crack widths, and with the adoption of staggered joint construction for the Primary Lining further help control the watertightness. To enhance the watertightness of the concrete, in particular at joints, the Primary Lining SCL mix will incorporate a waterproofing admixture where a crystallisation agent (additive) is used to promote self-healing.
within the concrete after placement. Compliance with infiltration and exfiltration through the shaft lining will be confirmed by numerical seepage (flow) analysis.

2.4 Durability Assessment

The durability assessment of the structural elements (permanent works) required extensive analysis, especially for the Secondary Linings durability modelling according to the fib standards. For SCL all potential deterioration mechanisms have been considered in relation to the exposure conditions in the ground. Prevailing ground and groundwater conditions were assessed and the ground classified as Design Chemical Class 3 (DC-3) in all strata and Design Chemical Class 2 (DC-2) in the London Clay Formation. For the base slab the exposure condition warrants Concrete Class DC-3 plus the use of an additional sacrificial cover, otherwise known as an Additional Protection Measure (APM).

The maximum crack width requirement is primarily related to the exposure conditions, magnitude of tensile stresses and the self-healing capacity of concrete. To meet durability requirements a crack width of 0.3mm is adequate for the exposure conditions assessed. Corrosion is not a consideration of SFR Concrete Linings, because they are in compression during the operational life of the structure. For Secondary Linings which contain fluid pressure, the structural crack widths have been limited to 0.2mm at the surface. This ensures the risk of reinforcement (where it is specified) corrosion with adequate cover will be minimal. At this level, crack widths enable the self-healing of concrete in a wet environment, albeit this is not relied upon in the design.

In order to enhance durability a sacrificial layer (APM) of 75mm for the Primary Lining and 150mm for base slab is provided. This layer is not considered within the structural thickness during design calculations. Additives are also included in the SCL mix in order to enhance interlayer and concrete matrix impermeability.

2.5 SCL Development & Trials

Significant effort was invested by MSES and BMB to design and develop the appropriate SCL mix specifically for Thames Tideway Tunnel. To this end early trials have been carried out to design the SCL Mix. Experience from previous infrastructure projects proved invaluable when designing the mix.

Pre-trials carried out at the supplier’s facilities established a C35/45 mix (CII-D+SR to BS 8500, with chemical class DC-2 ‘+’ APM) available for use on the West Contract of Thames Tideway Tunnel. The mix was designed to satisfy the design specification (compressive strength, residual flexural strength, permeability, workability). The target water cement ratio was set to 0.48 and the cementious content to 450 kg/m$^3$. The maximum coarse aggregate size was 6mm (granite).

High performance hooked end steel fibres (1800MPa yield strength, 65 aspect ratio) were used to enhance the short-term ductility and crack control capacity of the mix. Subsequent pre-commencement trials were also carried out to test the spraying equipment and the SCL performance (encapsulation) when applied against reinforcement.

Figure 3. Sprayed Beams and panels prepared for testing
It is common knowledge that the mass permeability of the SCL is very often controlled by the permeability of their construction joints; hence this is why a crystallisation agent (Xypex C500NF) admixture has been used to enhance the impermeability of the SCL joints. Although, the addition of this agent is not a substitute for a good quality dense concrete mix, the lab tests demonstrated that the addition of crystallisation agent shows a measurable improvement in the mass and the joint impermeability after water penetration tests were carried out.

Figure 4. The flexural tensile strength of the SCL Mix (from the works)

Tensile Strength (fib, 2013) is based on residual strength indices from the BS EN 14651 test. The Characteristic tensile flexural strength at $CMOD=0.5\text{mm}$ and $CMOD=2.5\text{mm}$ specified $f_{Rk}=2.3\text{MPa}$ and $f_{Rk}=2.1\text{MPa}$, respectively. The benefit of enhanced tensile capacity of the SCL is only considered during the early age and short-term conditions i.e. during construction. Therefore, SCL linings are assumed to have zero tensile strength in the persistent design situations. Where reinforcement is required to resist induced tensile stresses (e.g. at portal openings), steel bar reinforcement has been provided.

3 SHAFT SCL CONSTRUCTION

3.1 Shaft basal depressurisation

Depressurisation was required in the Lambeth Group for CARRR Shaft during excavation and SCL works. The purpose of the depressurisation is to ensure that pore pressures in the permeable layers are reduced sufficiently to avoid risk of basal heave.

At CARRR the standing groundwater level in the Clay within the UMB (Upper Mottled Beds) of the Lambeth Group (95.0mATD head recorded at a depth of 53-55.0mATD) has been shown to be above the lowest excavation level (56.05mATD). Measurements from additional boreholes revealed that the standing water level at the top of coarse-grained Upnor Formation (42mATD) was at approximately 83.0mATD and therefore would generate an uplift pressure greater than the resistance of the fine-grained Lambeth Group ‘plug’. This difference in pressure suggested that there was no certain hydraulic connectivity between the strata where the piezometer readings were taken and that the low permeability Clay in the LMB (Lower Mottled Beds) of the Lambeth Group in between was acting as an aquiclude.

A depressurisation plan was created in order to reduce the pore water pressure in the lower aquifer (in the confirmed coarse-grained strata below 45.0mATD). There was also potential water bearing soil layers suspected from Site Investigation data at the top of the Harwich Formation (59.5mATD - 59.0mATD) and a Silt layer at the top of the Lower Mottled Beds of the Lambeth Group (53.0mATD - 52.16mATD) which required investigation to confirm the pore water pressure and any hydraulic connectivity to the aquifer. The ground conditions and water pressures were verified from additional boreholes as part of the depressurisation works.
The depressurisation plan required deep wells in Thanet Sand, avoiding disturbing the Chalk, and was carried out in two stages:

Stage 1: 5No. Active External wells installed from ground level:
4No Thanet Sand Wells were installed and had a response zone from 44.5 to 34.5mATD and were actively pumping throughout excavation with the use of a pump installed at 36mATD. The flow for each well did not exceed 1.5l/s. 1No Well in Upnor Formation was also installed, which comprised a narrower response zone between 45.0-40.0mATD. The Upnor Well had a pump installed at 41mATD and yielded 0.7 l/s. All Wells at this stage were drilled from ground level and activated early on during construction; this enabled a drawdown in the shaft to a GWL of less than 75mATD to be achieved and subsequently allowed the drilling of internal wells.

Stage 2: Development of 7No. internal relief wells to depressurise the Upnor Formation and Thanet Sands.
These wells were developed at the locations shown in Figure 5 from a ground level of 78.5mATD and had a response zone between and 45.0mATD and 37.0mATD. During the initial pumping test phase the internal wells were flow tested and two wells, PRW4 and PRW6, were selected to be actively pumped with a pump installed at 37.5mATD and 38.5mATD respectively. During the course of the excavation flow from these wells did not exceed 2l/s. 5No of the remaining Wells acted as passive relief Wells, PRW1,3,5,8,9. Wells PRW2 and PRW7 were unsuccessful and subsequently were abandoned.

Furthermore, 2No. internal relief wells were installed, ILG1 and ILG2, with a response zone between 63.0mATD and 52.0mATD. These wells intended to relieve the potential excessive flows in the Harwich Formation and Upper Mottled Beds.
Overall the scheme was largely successful and enabled the construction of the base slab.

3.2 Shaft Excavation
The shaft was constructed using the sprayed concrete lining (SCL) method. This well-established method comprises of staged excavation of the shaft using mechanical excavation and the application of sprayed concrete to the excavated surfaces to provide ground support and create the lining thicknesses.
Due to the size of the shaft the thickness of the Primary Lining tapered up to a maximum of 1050mm. In order to construct these abnormally large thicknesses the sprayed concrete had to be sprayed in 3No. separate layers with each layer being 350mm thick. A Sealing Layer (also acting as the APM) was incorporated in to the first Layer, which helped provide the immediate ground support.
In order to help control the ground movements the amount of the ground excavated was limited by two main criteria:
The first was the advance depth; this was limited to a maximum of 1.2m high. This ensured a reasonable advance height and controlled the amount of open ground.
The second one was the excavation and spray sequence. The sequence started by bulk-excavating the centre of the shaft and leaving a berm in place to provide temporary support and prevent softening of clay. Each Berm was then removed and subsequently sprayed (the first layer only) for a section of the shaft (such as a quadrant). Once the first layer was complete the second and third layers were individually sprayed fully round the circumference of the shaft in order to minimise the number of vertical joints. This methodology was developed over years of experience of SCL construction in soft ground. In all cases staggered joints were formed.

3.3 Base Slab

The 2800m$^3$ base slab was designed with a flat top and domed base. It was designed as a slab of varying cross section to resist the uplift pressures generated from the groundwater and long term geostatic pressures. The slab was designed assuming no structural rotational or horizontal connectivity with the Primary and Secondary Linings. This consequently removed the need to provide reinforcement across the joint and hence provided benefits in terms of simplifying the connection details, improving the durability and watertightness. The joint is in compression and the rotations being transferred into the lining wall are limited; this removes restraint to horizontal
movements (expansion/contraction) within the base slab. FE thermal modelling was carried out to capture the heat of hydration development.

3.4 Launch and Reception Chambers

The shaft consists of three chambers, one chamber is for the launch of the main Tunnel Boring Machine (TBM) for the West Contract of Thames Tideway Tunnel and the other two chambers allow for the reception of TBMs (one smaller TBM from the Frogmore Connection Tunnel at a high level and one from the Central Contract of Thames Tideway Tunnel). The chambers are up to 10m wide and 55m long, plus each chamber will have a sprayed concrete steel bar reinforced portal constructed prior to the chamber construction. The bar sizes, spacing and layering take into account constructability considerations for encapsulation of reinforcement using the SCL method. The use of reinforcement couplers are employed where appropriate to assist with constructability of the larger portals during staged construction.

3.5 Ground Movements and monitoring

Extensive monitoring has been carried out at surface. The overall movement due to excavations was within the predictions, which were derived from empirical and FE Analysis capturing the effects of construction activities, excavation, soil consolidation and dewatering. The SCL deformations were within the ‘Green’ Trigger value (radial - 5mm) with one exception at the south side at mid shaft level, where ‘Amber’ Trigger levels were reached (radial - 8mm).

![Figure 9. Surface settlement variation with time.](image-url)
4 CONCLUSIONS

The Thames Tideway Tunnel has constructed the largest ever built SCL shaft in the UK in soft ground. A new SFR mix with enhanced watertight features has been adopted and successfully applied by controlling the construction sequence. Ground movements and lining deformations were within the predicted values.

5 ACKNOWLEDGEMENT

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