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The innovative use of fabric formwork for tunnel infilling at an historic London landmark redevelopment

Utilisation innovant de coffrages en tissu geotextile pour le remplissage des tunnels, à un réaménagement historique de Londres

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ABSTRACT: A major inner city redevelopment is taking place on the site of a decommissioned coal-fired power station located on the south bank of the River Thames, in South West London. Following its closure the site has become one of the best known landmarks in London with its iconic brickwork and four white Grade II* listed chimneys. At the time the site was taken over for construction of a major mixed-use development, the precise location and condition of the many underground structures including the redundant cooling water tunnels was unknown. These hidden structures constituted a significant risk of delay, disruption and additional cost to the high profile project.

A systematic process of investigative probing was employed to establish the position, diameter and condition of the cooling water tunnels. The crowns of the 3.3m diameter tunnels were located at depths of 13 & 17 metres below the working platform, several metres below the River Thames. Subsequently an innovative solution was implemented to seal off the tunnels using bespoke fabric formwork stop-ends (largest reported size) that were installed remotely from the surface via 508mm diameter boreholes. Once in position each plug was inflated with the required volume of cement grout and verified by monitoring sensors.

The solution avoided the need for extensive temporary works and excavation, delays and significant additional cost to the project as well as ensuring that secant piling operations were not interrupted. This solution subsequently enabled the tunnels to be safely infilled with minimal environmental impact and eliminated the risk of river water flooding into the basement excavation.

RÉSUMÉ: Un important réaménagement du centre-ville est en cours sur le site d'une centrale électrique au charbon, mise hors service, située sur la rive sud de la Tamise, au sud-ouest de Londres. Après sa fermeture, ce site est devenu l'un des monuments les plus connus de Londres grâce à ses briques emblématiques et ses quatre cheminées blanches classées Grade II* . Lorsque le site a été repris pour divers projets de construction, on ignorait l'existence et l'emplacement exact de nombreux ouvrages souterrains, dont les anciens tunnels de canalisations de refroidissement d'eau. Ces structures cachées pouvaient générer beaucoup de retard, de perturbation et de coûts supplémentaires à ce projet de grande envergure.

Afin de déterminer la position, le diamètre et l'état des tunnels de canalisations d'eau de refroidissement, on a exploré l'ensemble des sous-sols à l'aide de sondes. Les couronnes des tunnels de canalisations de 3,3 m de diamètre étaient situées à des profondeurs de 13 et 17 mètres sous la plate-forme de travail, à plusieurs mètres sous la Tamise. On a donc dû mettre en place une solution innovante pour sceller ces tunnels, en utilisant des butées de coffrage en tissu sur mesure (les plus grandes possibles), installées loin de la surface grâce à des trous de forage de 508mm de diamètre. Une fois en place, chaque bouchon était rempli avec la quantité de ciment voulue, puis contrôlé par des capteurs.

Cette solution permettait d’éviter des travaux temporaires et d'excavation de grande envergure, les retards et des coûts supplémentaires importants au projet, tout en garantissant que les opérations d'empilage sécant ne soient pas interrompues. Grâce à cela, on a ensuite pu remplir les tunnels en toute sécurité avec un impact minimal sur l'environnement et empêché les inondations de la rivière dans l'excavation du sous-sol.

1 INTRODUCTION

Since the closure of the former power station in 1983, the site, which is located on the south bank of the River Thames, London, has remained derelict and largely unused despite several attempts to redevelop the area.

The iconic buildings and the 42 acre site are now being redeveloped into a mixed use commercial and residential zone close to central London with improved transport infrastructure including a new metro station and river taxis.

The development area located between the north of the main building and the existing River Thames wall was previously used for coal storage. A new basement structure will be constructed within a new retaining wall cofferdam comprising sheet piles and rotary bored secant piles installed through a sequence of made ground, alluvium, river terrace deposits and stiff overconsolidated clay.

The new basement is underlain by 2 live electricity cable tunnels, 3 disused cooling water tunnels, a large number of redundant piles, retaining walls and concrete structures. It was considered possible that the cooling tunnels could allow river water to flood the basement excavation and that they could be damaged by the planned construction activities.

In order to safely construct the secant piled retaining walls and excavate the site to construct the basement the cooling water tunnels needed to be isolated from the river and subsequently infilled.

Above ground, the tunnel infilling operations were constrained by the need to interface with many other site activities and maintaining unhindered access through the worksite.

2 INVESTIGATION WORKS

2.1 Initial desk study and surveys

Although a considerable number of site surveys and geotechnical investigation boreholes had been undertaken across the worksite, no detailed information relating to the precise extent and location of the cooling water tunnels was available. Historical drawings of the existing tunnel locations were obtained which helped to determine where the new basement retaining walls were likely to conflict with the existing structures.

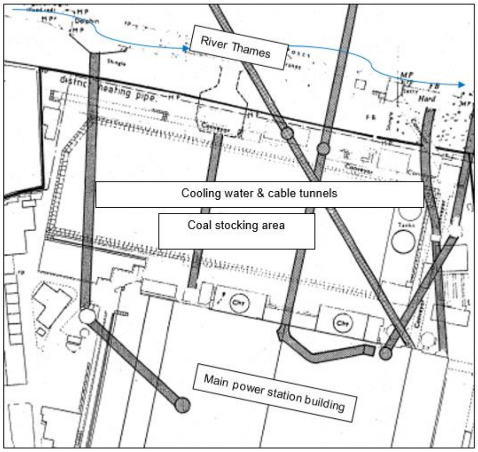

Figure 1. Former Power Station cable & cooling water tunnels adjacent to River Thames

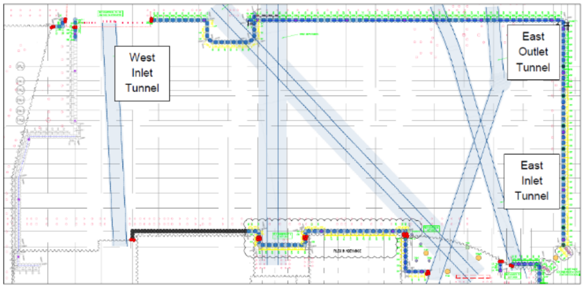

Figure 2. Proposed deep basement and existing tunnels

Where it was possible to gain access, the client had entered and surveyed the existing cable tunnels and West Cooling Water inlet tunnels. This gave useful knowledge as to the likely diameter and construction materials of the East Cooling Water tunnels. These tunnels were believed to be constructed using cast iron segments inlaid with concrete infill panels to provide a smooth internal finish.

In consideration of the ability to drain water, safely access and accurately survey the West Inlet tunnel and the close proximity of its' crown to the proposed basement formation level, the client elected to infill with an inert granular backfill material upon excavation. The East Cooling Water tunnels were deeper and more challenging.

2.2 Advance probing

In order to gain more accurate information, a systematic programme of probing was undertaken to establish the cooling water tunnels alignment, depth and dimensions.

A series of small diameter probe holes (Fig.3) were drilled vertically perpendicular to the anticipated tunnel axes and invert depths. This exercise confirmed the expected tunnel diameters (3.6m or 12 feet).

This survey provided important information for the infilling of the tunnels but also the construction of the secant piled retaining walls and bearing piles within the proposed basement.

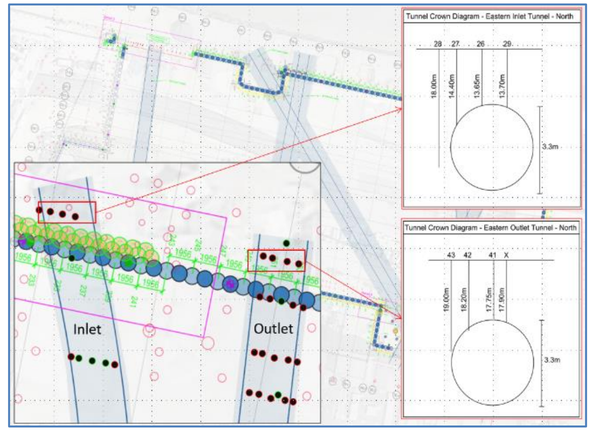

Figure 3. Advance probing above secant pile retaining wall alignment to locate cooling water tunnels

2.3 3D Sonar surveys

Once the approximate cooling water tunnel locations were known, it was then possible to drill into the tunnel crown at a number of positions to enable a sonar survey to be carried out.

This survey was intended to provide more detailed knowledge of the tunnel alignment and depth of any debris or deposits contained within the tunnel bores. The survey results enabled a more detailed assessment of the likely volume of infill material required to infill the tunnels.

The survey holes were formed at 100mm diameter using a conventional rotary-percussive rig to drill a temporary steel casing down into the tunnel crown (locations shown on Figure 4) and install a sacrificial borehole liners prior to extraction of the steel drill casing.

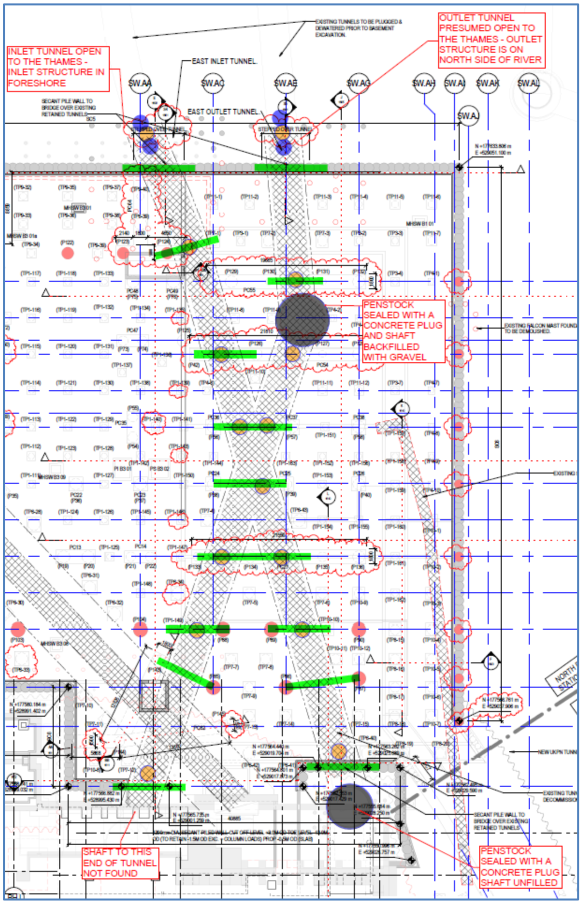

Figure 4. Advance probing and 3D sonar survey hole positions to establish cooling water tunnel data

The surveys were undertaken by Geoterra and collated for later interpretation and comparison with available as-built information.

2.4 Survey results

The probing and sonar surveys provided the necessary information to develop the proposed cooling water tunnels infilling solution.

Tunnel diameters	3.3m internal
	3.6m external
Tunnel depth to crown	13.0m Inlet
	17.0m Outlet
Tunnel infilling volume	1,257 m^3

It is notable that during drilling works on the East Outlet tunnel crown, a sudden outflow of gas, believed to be hydrogen sulphide, was recorded. Following this event, the gas was allowed to vent freely and gas monitors were used for all subsequent drilling and investigation works.

Due to programming and access constraints, the East Inlet tunnel crown was not drilled during the advance probing phase and no details obtained regarding the nature of its contents. It was therefore initially assumed that the Inlet tunnel would require a similar volume of infill materials.

3 SOLUTION DEVELOPMENT

Once the positions of the East Cooling Water tunnels had been established, further consideration was given to the infilling operations.

The probing confirmed that both tunnels had been constructed within the underlying stiff clay and that the Outlet tunnel contained a layer of silty debris, water and gas or air.

3.1 Tunnel infilling considerations

Due to the significant depth of the redundant tunnels, in excess of 13m below the working platform and the concern that the tunnels could be directly connected with the River Thames, it was not considered practical or economic to construct access chambers to facilitate infill operations.

In order to overcome these challenging constraints a means of remotely plugging the tunnels by injecting self-hardening cementitious materials into bespoke fabric formwork bags (Figures 5&6) was developed by Cementation Skanska in collaboration with their supply chain partner, Proserve Marine.

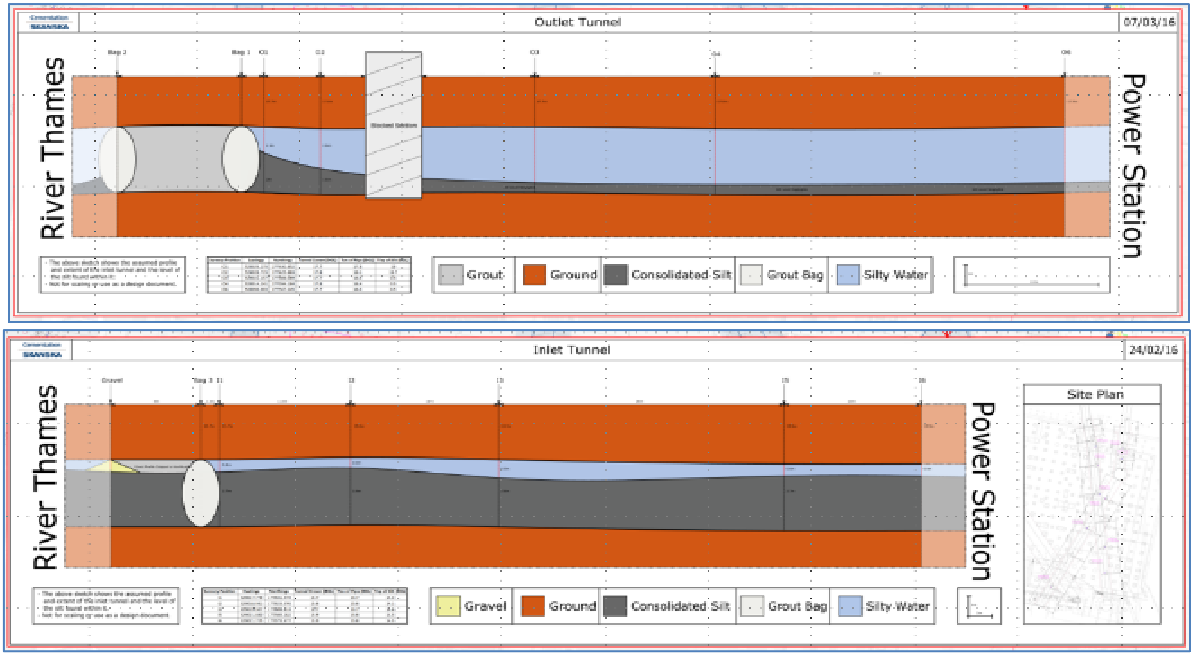

Figure 5. Longitudinal section of cooling water tunnels showing silt, water and stop-end positions

The use of fabric formwork is well known within the marine construction industry with many applications involving placement and infilling operations underwater and requiring remote sensing to confirm successful installation.

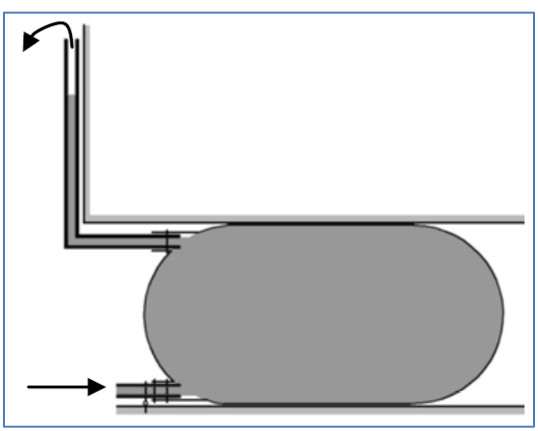

Figure 6. Fabric formwork infill seal concept

3.1.1 Key risks identified

Tunnel collapse and ground instability

Uncontrolled release of contaminants into the River Thames

Release of construction materials from the tunnels into the River Thames

Surcharging of the River Wall by construction plant

3.1.2 Stop-end (bulkhead) concept

In simple terms each cooling water tunnel comprised a segmental cast iron cylinder running horizontally from beneath the existing power station building, beneath the worksite and existing river wall and river bed and connected to a screening chamber located in the river channel.

In order to target the placement of cementitious infill materials in the tunnel directlty beneath the secant pile wall alignment, 2 fabric formwork bags were to be placed at a separation of 10m along the tunnel axis.

These bags were to be inflated to form spherical plugs within the tunnel and create a controlled zone into which a cementitious grout could be placed. The bags were constructed to be approximately 10% larger than the tunnel diameter to ensure that a tight contact against the tunnel lining would be achieved.

The fabric formwork plugs would mitigate the risk of grout losses into the river or dilution due to the water contained within the tunnel bore.

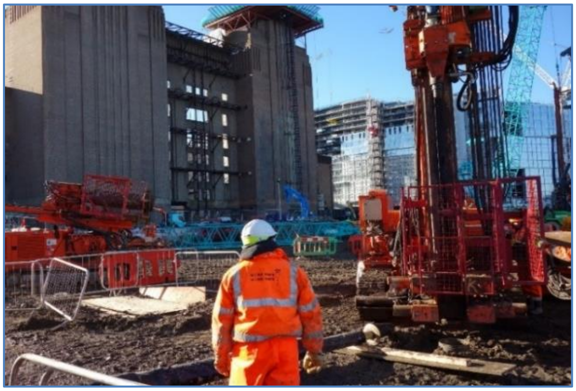

Figure 7. Drilling to tunnel crown for placement of fabric formwork

3.1.3 Tunnel infilling concept

Following successful placement of the tunnel stop-ends, the cooling water tunnels could then be infilled with a cement bentonite grout mix using bulk grouting techniques.

At the development stage it was suggested that it would be possible to use the waste water extracted from the redundant tunnels for use in grout mixing. Although the water quality would need to be tested and result in some additional pumping costs, this would likely result cost savings and negate the need to dispose of waste water from the site.

The grout was to placed via the holes formed to undertake the 3D sonar survey and these holes could act as air vents and allow trapped water to be expelled from the tunnels.

3.2 Stop-end construction

3.2.1 Formation of stop-end holes

A Klemm 709 mini-piling rig was used to install 508mm diameter temporary steel casings through the overlying made ground and alluvium to the tunnel crown. The drilling then continued to penetrate the tunnel lining and terminated a short distance below the crown.

Figure 8. Drilling operations for creation of stop-end holes in advance of fabric formwork placement

3.2.2 Placement of fabric formwork into tunnel bores

The fabric formwork bags were manufactured in factory conditions using a geofabric with a suitable tensile capacity and internal diaphragms that were capable of withstanding the grout fluid pressures caused during inflation.

The formwork bags delivered to site wrapped around a specially fabricated sacrificial steel mandrill and secured in place with cable ties.

This was then carefully lowered to the correct depth using the drilling rig.

Figure 9. Fabric formwork preparation for placement into stop-end locations

Once in the required position, a grout injection pipe was attached and a cement-bentonite grout mix (water:cement ratio of 20:1 with a target flow of 45 seconds, a density of 1.3g/cm^3 and a 28 day cube strength of 1N/mm^2) to inflate the bag.

In order to control the inflation process, the mandrill was fabricated with grout ports positioned at the lowest point. As the grout exited the mandrill it forced the grout bag open from the base breaking each cable tie and increased the likelihood of an even infilling process from the bottom upwards.

To provide further control of the infilling process, grout (conductivity) detectors were fixed close to the top of the fabric formwork bag. These enabled the site team to be notified of the completeness of each grout inflation operation.

3.3 Fabric formwork placement checks

3.3.1 Grout volume verification

The volumes injected were compared against the theoretical volumes expected as a simple check. These indicated that 2 out of the 4 fabric formwork bags installed had inflated correctly with approximately 30m^3 of grout in each bag.

The bags installed within the Inlet tunnel could only be inject with 17m^3 and 4m^3 compared to a theoretical volume per bag of 20m^3.

Figure 10. Grout injection and inflation of fabric formwork stop-end

Verification holes were drilled though the tunnel 1m from the bags insertion point. These holes were then probed with a weighted line to confirm the bags location.

3.4 Stop-end placement difficulties

Significant difficulties were experienced during infilling of the first Inlet tunnel stop-end. Despite the successful placement of the fabric formwork wrapped around its mandrill, the grout injection volumes were much lower than expected. Further checks were carried out to establish the conditions within the tunnel and it was found that the silt levels were much higher than originally expected.

It was therefore considered that the high silt levels had prevented the fabric formwork from opening fully to fill with grout.

Given the high silt level it was agreed with the client that the gap between the top of the silt and the tunnels crown would be infilled with sand.

Sand was placed through 5 drilled holes spaced at 0.50m intervals along the tunnel axis. The theoretical volume required was calculated based on the size of the gap and the sands angle of repose.

3.5 Supplementary measures for East Inlet tunnel

Following an depth review of the conditions encountered it was decided that it would be possible to employ jet grouting techniques to modify the silt deposits contained within the tunnel. Although no in-situ test data was available for these deposits, conservative jet grouting parameters were adopted which had been employed to construct the grout interface seals within medium dense river terrace deposits elsewhere on the Battersea Power Station worksite.

Six jet grout columns were constructed from the tunnel invert to the crown level thus forming a hybrid of grout/soil mix and grout infilled fabric formwork beneath the secant wall alignment.

The potential environmental risks associated with this approach were considered to be acceptable in view of the tunnel bore being almost completely full of silt.

The zone between the stop-end locations was drilled and injected with further cementitious grout and subsequently re-drilled to confirm that the no further voids were present and an effective plug had been formed in the tunnel.

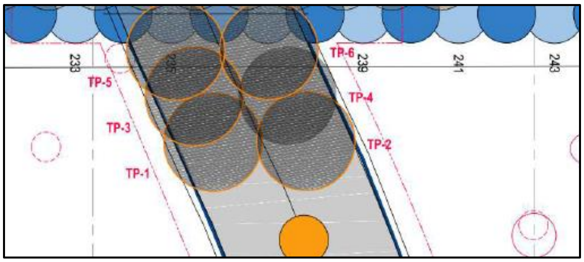

Figure 11. Plan view indicating supplementary jet grout column positions to complete stop-end seal within cooling water inlet tunnel

Figure 12. Jet grouting rig constructing soil-grout columns within the cooling water inlet tunnel

3.6 Tunnel infilling

Upon confirmation that the stopends were completed the bulk infilling operations were carried out satisfactorily. The total grout volume placed in the tunnel was reported as 800m^3.

4 CONCLUSIONS

The project demonstrates the importance of a comprehensive understanding of a site history, ground conditions and the effects that unexpected conditions can have.

Figure 13. Grout batching for bulk infilling operations

The new development was already underway without a clear knowledge of the buried legacy of tunnels that posed a threat to the construction of the retaining walls and deep basement structure.

Despite the challenging conditions, an innovative solution was developed by effective collaboration, combining a number of ground engineering techniques in a systematic way and by careful observation at each stage.

The project was successfully completed and low permeability infill materials placed into the tunnel voids at minimal risk of excess grout loss, environmental damage or impact on the basement construction operations.

Recent developments in remote surveying and scanning technologies could be employed to enable the further use of this approach for construction of seals and barriers in tunnels, chambers or natural cavities.

5 ACKNOWLEDGEMENTS

Many thanks must go to colleagues for their interest, support and contribution to the delivery of this solution. In particular our late colleague Ian Bleything was a key member of the site team who enthusiatically took on this unusual concept and implemented a safe and practical solution.

We were also greatly assisted by Martin Hawkswood and colleagues at Proserve Ltd who designed and manufactured the fabric formwork which formed an integral part in the successful construction of the stop-ends.