Urban Tunnelling: The Vauxhall Underground Station Upgrade

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3. Conventional Tunnelling Methods in Development and Use

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1. Introduction

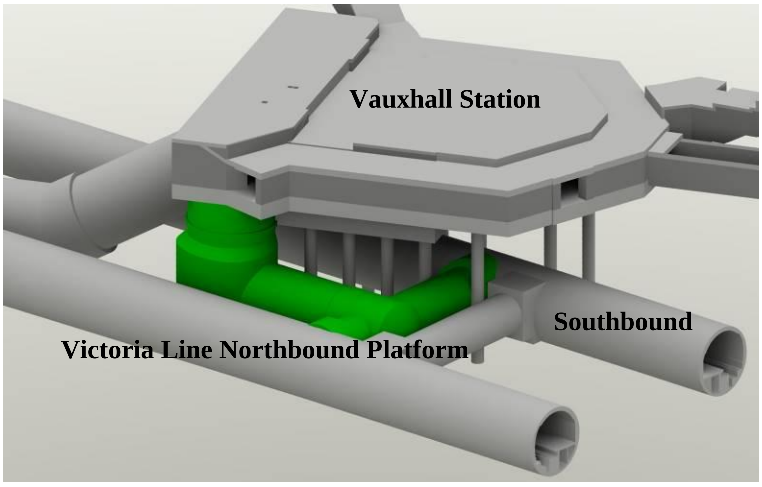

***Fig. 1** New SCL shaft & tunnels for Step Free Access (green).*

The Vauxhall Station Upgrade project is currently under construction in London, UK by Bechtel Ltd. (Bechtel) as the main contractor, with Sprayed Concrete Lining (SCL) designed by Gall Zeidler Consultants (GZ) in a design-build procurement model. A mandate of London Underground (LU) is to provide Step Free Access for disabled customers in any station which undergo upgrade schemes. To provide this access at Vauxhall Station, a new SCL shaft and tunnels are being built to connect to the existing station ticket hall with the platforms. Avoiding time consuming and costly utility relocation, the SCL works are currently being constructed from within a disused bin store of the station, with no direct access from the surface. Geometrical constraints necessitated that the SCL construction occur within close proximity to existing station structures and underground platform tunnels, all of which were required to remain in full operation during the works. This paper presents the design and construction challenges which were encountered during the project and are specifically unique to tunnelling in a dense urban setting such as London.

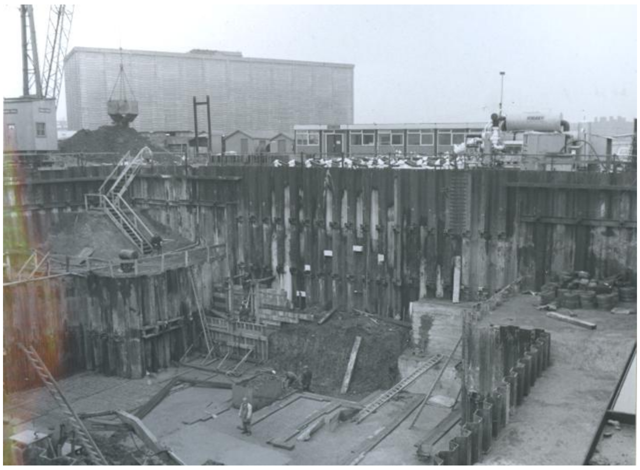

***Fig. 2** Archive photograph of station construction, 1969 (courtesy LU).*

2. Project Area

Vauxhall Station is located in southwest London, directly adjacent to the River Thames, at the intersection of Wandsworth Road and Vauxhall Bridge Road. The majority of SCL construction was expected to occur within the London Clay formation underlying the existing station. The upper two metres of the new SCL lift shaft is located within water-bearing gravels.

The station was built in 1969 within a steel sheet pile cofferdam to allow for construction of the station below the water table and partially within gravel material hydraulically connected to the river (see Fig. 2). This cofferdam was abandoned in-place after the construction of the station. The area directly above the escalator barrel was frozen to excavate the escalator barrel, which suggested general instability of the gravels.

The proposed location for the new SCL shaft was conveniently located within the existing cofferdam, which the project utilized in order to partially stabilise the gravels and provide a partial water cut-off in the porous gravel material.

3. SCL Design

A RIBA Stage D level conceptual design was distributed to prospective contractors with the Invitation to Tender documents. The RIBA D design proposed excavating and partially demolishing the existing bin store in order to construct the new lift shaft. This included removing part of the existing station roof and rerouting numerous utilities above the station.

The existing sheet pile cofferdam would be partially reused and new bored piles installed for support of excavation. Connections to the existing platform tunnels would be performed with classical segmental lining and squareworks methods. Tube-a-manchette (TAM) grouting was considered to be required for compensation grouting for protection of the existing LU station structures, as approximately 170mm of ground settlement was expected from the tunnelling works.

GZ and Bechtel devised an alternate construction method, in which the existing station structure was effectively used as pre-support for the overlying utilities. An 8.1m by 8.6m elliptical SCL shaft was designed to be excavated from within an existing disused bin store, which was then enlarged after approximately 6m depth to an approximately 9.6m to accommodate space requirements at the bottom of the proposed lift. The smaller section at the top of the lift shaft allowed for excavation to occur almost entirely within the existing sheet pile cofferdam. A 6.7m diameter adit tunnel and two 5.1m diameter cross passages would be constructed from the lift shaft to provide connections to the existing platform tunnels.

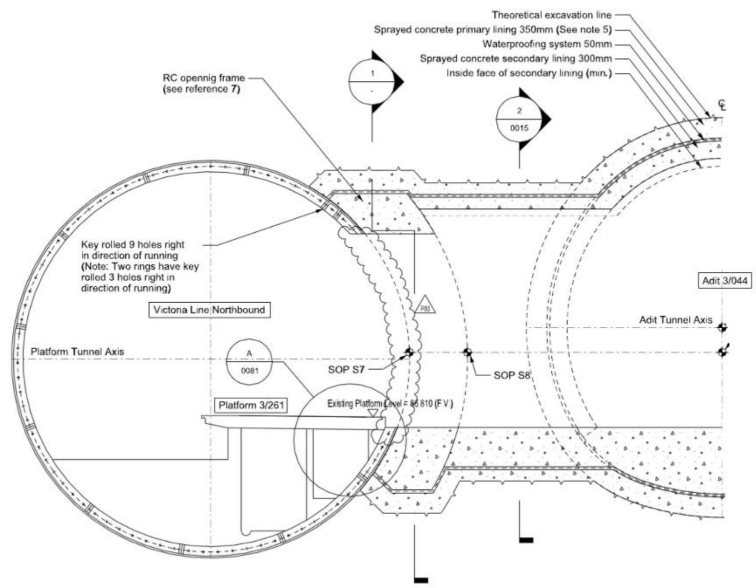

Fig. 3 SCL connection to existing platform tunnels.

SCL construction was chosen for the underground structures because of its geometric flexibility and its ability to provide immediate ground support to limit ground movements and surface settlements, and in particular, the existing LU assets. All SCL construction would occur within very close proximity (less than 1m) to the existing platform and cross passage tunnels. Platforms were required to remain in full operation during construction. Connection to the cast iron platform tunnels was designed without the use of internal props by selecting an SCL excavation and support sequence to limit movements of the platform tunnels.

SCL primary linings ranged in thickness between 200mm and 250mm, and were primarily steel fibre reinforced. Areas around the tunnel junctions were locally thickened to 350mm at the cross passage openings, and 500mm at the shaft breakout. Long term ground support was provided by a steel fibre reinforced secondary lining between 200mm and 300mm in thickness, installed with sprayed concrete in the lift shaft and cast in-situ concrete in the horizontal tunnels.

The connection with the existing platform tunnels was designed with a reinforced concrete collar, rather than steel lintel beams typically installed over new openings in cast iron tunnel linings, as a more economical and easier to construct solution. Threaded steel rods transfer thrust loads in the platform tunnel linings into a reinforced concrete arch over the new opening.

Extensive three-dimensional finite element modelling and potential damage assessments were performed for the structures to evaluate loads predicted in the SCL linings and to determine the influence of ground movements on existing structures and nearby utilities. Based on conclusions drawn from these analyses, it was determined that internal props to the cast iron platform tunnel linings were not required for construction of the SCL cross passages.

Maximum surface settlements conservatively estimated by the potential damage assessment were approximately 22mm. Negligible movement was predicted for nearby third-party and London Underground assets. One utility – a 36-inch (914mm) diameter medium pressure gas main – was identified as potentially sensitive to the predicted ground movements and was decommissioned prior to tunnelling works began.

4. Site Set-Up

4.1 Shaft Access

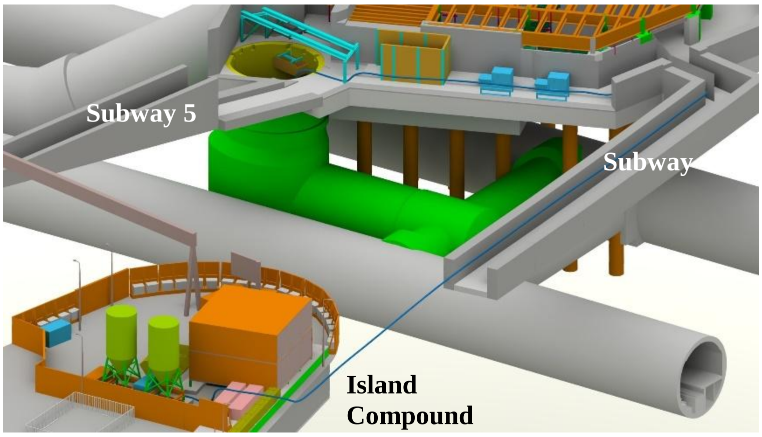

Fig. 4 *Site set-up; Island Compound and site access.*

The main site compound, Island Compound, is located between Wandsworth Road and Bondway with connection to the shaft via Subway 4. It is here where the site welfare facilities and associated SCL equipment are located (see Fig. 4). Concrete is pumped from two CPI Euromix Silos (22m^3 each) down Subway 4 to a Meyco Suprema pump stationed within the corridor of Vauxhall station. From here, the concrete is pumped farther down the corridor and into the SCL shaft to the excavation face for application. In total, concrete is pump approximately 90m from the silos to the face along a route that consists of numerous bends.

The SCL Shaft is located at the base of Subway 5 (see Fig. 4), which provides a second means of construction access from the St. Georges Wharf compound. The extraction-only ventilation system, as well as additional SCL materials and equipment, is located within the St. Georges Wharf Compound. For this project, the extraction-only system was chosen because it provided sufficient ventilation during all aspects of the works, as well as reduced the amount of plant equipment required on site.

Intermediate load-bearing walls were present in the bin store where the shaft would be constructed. New steelwork was installed in the bin store to allow for removal of the structural walls, which had to be framed around the new lift location, as there was no clearance between the top of the lift and the existing roof. Steelwork was erected and the load-bearing walls were removed prior to tunnelling works commencing.

Complicating construction, the lack of vertical clearance in the bin store had ramifications in many other instances with the equipment and techniques, which could be used for shaft and tunnel construction. The selection of excavation equipment, drilling equipment, crane, and sprayed concrete equipment were all partially influenced by the limited head room above the shaft. Many tasks required bespoke equipment to be designed (i.e. the gantry crane) in order to be used at Vauxhall.

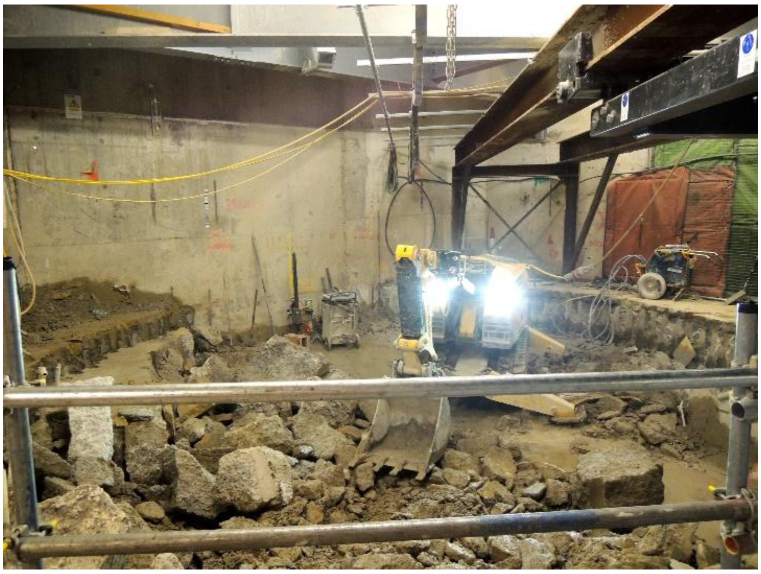

Fig. 5 *Gantry crane installed above the SCL shaft.*

4.2 Gantry Crane and Shaft Decking

In order to facilitate construction of the SCL Shaft and Tunnels, a temporary 3 tonne gantry crane was installed. The framework for the gantry crane spans from the corridor to the northwest corner of the disused bin store (see Fig. 5). The gantry crane's main use is for muck removal, but has also provided a means to lower machinery and equipment into the shaft.

No usable floor space at the bin store level was available after the shaft construction had begun, and therefore a shaft access platform was installed after approximately 4m of shaft excavation. This platform covered the top of the shaft with openings for skip removal and ladder access.

4.3 Muck Removal

Muck is removed from the shaft using an approximate 1.5m^3 skip, which is lowered and raised by the gantry crane. Once the skip is loaded and lifted out of the shaft, the gantry crane travels along the beams from the middle of the shaft into the corridor and unloads. From here, a Bobcat loader will either take the muck up Subway 5 to a 30m^3 skip at the top of St. Georges Wharf Compound to temporarily store the excavated material or store it in the muck bin located in the corridor. Once the 30m^3 skip is full, a Hi-Ab Grab Lorry empties the skip and removes material from site.

5. Construction

5.1 Slab Removal

Breaking through the existing station bin store floor required removal of almost 1.8m of concrete thickness. This concrete removal included a 200mm blinding layer, an 800mm thick reinforced concrete floor slab, a 700mm thick infill concrete slab, and an 80mm top layer. Slab removal consisted of hydraulic bursting from within a series of 107mm diameter core holes. A hit-and-miss core hole approach was used around the perimeter of the shaft to create the profile. Within the shaft profile, the core holes were spaced at approximately 500mm centre-to-centre.

Hydraulic bursting was chosen to allow for quiet and low vibration breaking of the concrete to prevent disturbance to the public, both in the station and at street level. A hydraulic breaker, attached to the Brokk 260 excavator, reduced the size of the broken concrete blocks for removal from site.

5.2 SCL Shaft Excavation and Support in Gravels

Once the slab was removed, the shaft excavation could continue. To enable construction through the waterbearing gravels, grout was injected along the perimeter of the shaft. An additional row of grouting lances was installed at the base of Subway 5 – the only location where the sheet piles were not present. Grouting pressure was limited to a maximum of 4 bar in order to avoid detrimental effects on the surrounding LU assets.

The purpose of grouting was to reduce water ingress into the SCL Shaft and avoid undermining the floor slab during excavation, and a two-component acrylic resin was selected. The acrylic resin was injected at an average of 2 bar pressure and was cut off when the intake rate was at a minimum or when the pressure exceeded 4 bar. To avoid washing away of the material during injection, the resin was mixed with a low dosage of accelerator to speed the setting time. The material was mostly successful in stabilising the waterbearing gravels; however, some local

Fig. 6 *Sheet piles exposed beneath structural slab.*

running of ground was encountered. As a result, a combination of dewatering lances and sump pumps were installed within the shaft to temporarily lower the groundwater table.

Excavation with a Brokk 260 through the 2.2m gravel stratum commenced in two vertical lifts, a 1.2m lift followed by a 1m lift. Each lift was excavated in 14 partial rounds. The initial step was to remove the central core – approximately 5m in diameter – with battered sides to the gravels' angle of repose. After each subsequent partial round, the exposed ground was sealed with 75mm; the primary lining (250mm) was sprayed after two consecutive partial rounds. Due to the lack of space within the shaft and the inability to lift large equipment in and out of the shaft frequently, it was decided sprayed concrete support be applied by hand.

As discussed above, the SCL Shaft was located within an existing cofferdam. However, there were locations where the sheet pile wall infringed upon the shaft profile. During excavation within the gravels, the ground was sealed prior to the removal of the steel piles. Ground material was removed to expose the face of the sheet pile wall and the sheet piles were burned out with a torch. Fill concrete from the station wall construction was present behind the sheet piles and was removed with a hydraulic breaker to the shaft excavation line (see Fig. 6). The sheet pile wall was removed from with the shaft profile until the toe level of the pile, approximately 5m below the station structural slab.

Fig. 7 *Shaft excavation of the central core.*

5.3 SCL Shaft Excavation and Support in London Clay

The transition from the waterbearing gravels into London Clay was excavated in three partial rounds with the primary lining installed after each partial round. Due to equipment constraints, the remainder of the SCL Shaft excavation through the London Clay proceeded with excavation of a central 6m diameter core prior to excavation of the remaining round in two sections (see Fig. 7).

With this approach, the entire 1m lift was excavated and supported within three consecutive shifts. Excavating the central core to 1m from the theoretical excavation profile allowed bulk mucking for the first shift. The following shift would dig half of the shaft to profile and spray the primary lining. The final shift excavated and supported the remaining half of the shaft.

Fig. 8 *Breakout of Adit tunnel top heading.*

Upon completion of the SCL Shaft, a temporary Alshor decking was erected to gain access to the Adit Tunnel Top Heading. The decking was approximately 4m in height and was built in two halves to suit site logistics. After the first half of the deck was erected and received a permit to load, the Brokk was lifted up from the shaft bottom by the gantry crane and lowered onto the temporary decking. After both halves were complete, a Meyco Oruga concrete spraying robot was lowered in pieces and assembled for usage in the tunnel construction.

5.4 SCL Adit Tunnel Excavation and Support in London Clay

SCL tunnelling continued for the Adit tunnel by coring through a 'soft eye' of the locally thickened and reinforced shaft lining, and breaking out the top heading (see Fig. 8). The entire top heading was advanced in 1m rounds to the Adit headwall before excavation of the invert, while installing a 150mm thick temporary sprayed concrete invert. After completion of the top heading, the invert excavation was advanced in 2m rounds. For the sprayed concrete application in the top heading, the Oruga concrete robot was used, which allowed for maintaining of a personnel exclusion zone close to the excavation face beneath wet shotcrete, reducing the risk of injuries due to concrete fallout.

6. Instrumentation and Monitoring

The new tunnels' close proximity to existing London Underground and other third-party stakeholder assets necessitated a thorough instrumentation and monitoring scheme. A high rise residential building, St. George's Wharf, is located within the LU-defined 6m zone of influence of the tunnelling works. Optical reflectors were installed on the building façade and read by an Automated Total Station (ATS) located with a clear line of sight to the entire building. Close coordination with the building owners and tenants was required and engineers representing the owners were involved in developing the instrumentation and monitoring proposals.

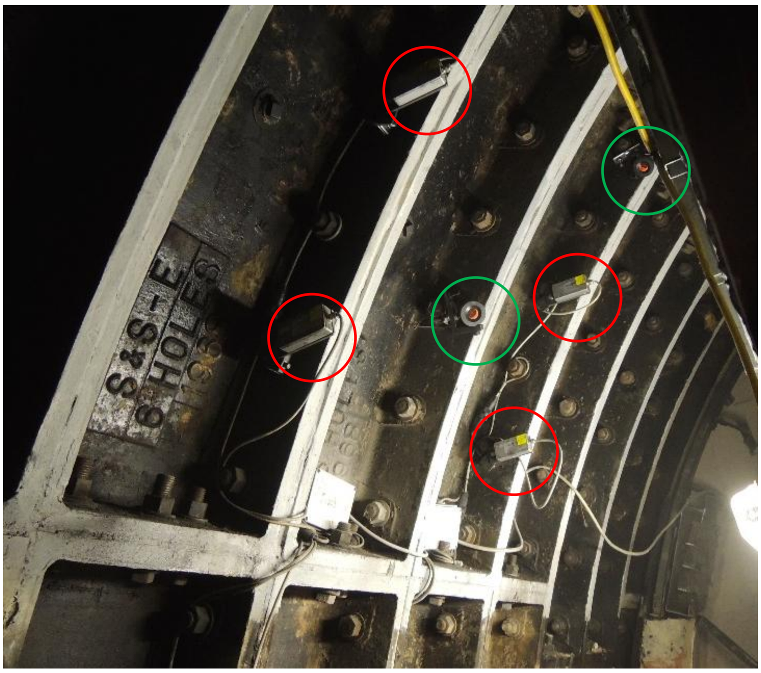

Fig. 9 *Breakout tilt meters (red), optical targets (green).*

The most sensitive structures to the predicted ground movements were the platform tunnel linings. Circa 1969, the platform tunnel linings are constructed of grey cast iron and are notoriously brittle when tensile stresses are introduced. During the construction of the cross passages, the platform tunnels were predicted to deform outward, towards the approaching cross passage excavation, resulting in increased bending moments and stresses in the linings. Typically, behaviour of the platform tunnels was monitored with optical targets installed in the crown around the tunnel perimeter, which were read by ATS. However, hoardings were installed at the breakout locations for the cross passages which did not allow for line of sight to the ATS. Therefore, two arrays of five tilt meters were installed

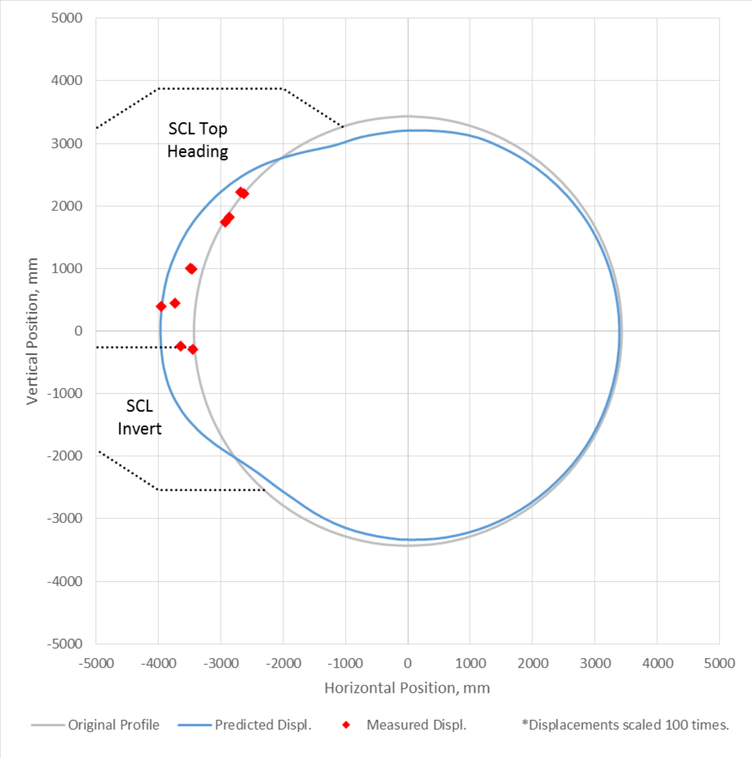

Fig. 10 *Comparison of predicted to measured platform tunnel displacements after primary lining construction.*

at each breakout location and deformations of the platform tunnels observed via deflections calculated from the resulting tilt readings (see Fig. 9). Manual readings from the optical targets were conducted once a week to compare to the readings taken from the tilt meters. This method worked well and proved to be more precise than the optical targets and ATS measurements and did not require a line of sight.

As can be seen in Fig. 10, an analysis of measured displacements correlates well to those predicted by the finite element analyses performed for the design. During the construction of the SCL cross passage primary lining, a maximum lateral displacement of 5.6mm was observed at the time of publication. This movement was well within allowable trigger levels and in line with the predicted behaviour of the structure and no damage was observed in the cast iron tunnel linings.

7. Conclusion

The Vauxhall Station Upgrade project posed challenges which are unique to tunnel construction within an urban environment. In such projects, the most challenging aspects are typically at interfaces with existing assets and coordinating with various stakeholders in the project to assure them that the impacts will be acceptable. Vauxhall's primary challenges involve logistics of setting up a tunnelling production site within a confined space and minimizing impacts of tunnelling on surrounding structures.

Choosing to build the SCL structures from within the disused bin store, rather than from surface level, allowed construction to progress without partial closure of Wandsworth Road. Noise and environmental impact on the surrounding area was limited and utility relocation was avoided. The chosen approach created logistical issues that prevented the use of standard shaft sinking equipment.

During construction, the project team implemented a system focusing on the quality of the concrete prior to its application. During the winter months, water has been preheated before it is mixed with the CPI Euromix, which provides optimal concrete temperatures at time of batching. Prehearing the water, as well as applying the sprayed concrete in thinner layers, has proven successful during the early strength development of the concrete and has helped the project avoid fallouts.

As of the publication date, SCL excavation is nearly complete, with an anticipated completion of tunnelling in February 2015. Further discussion on the project's conclusions will be presented at the conference.