# UK high-speed rail project HS2 – Safe, efficient and smart EPB tunnelling in London

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ABSTRACT: HS2 is a vital investment in Britain's future, aiming to develop a modern railway for fast, frequent, and reliable travel. It supports the government's goal of upgrading UK railways and enhancing journeys across the country. Phase 1 connects London and Birmingham, serving about 30 million people. The Skanska Costain STRABAG Joint Venture (SCS JV) is responsible for building the London Tunnels segment of HS2 and is unique among sections for exclusively using Earth Pressure Balance (EPB) TBMs. The complexity of this work requires the JV to develop new methods and technologies that transform the construction industry for future generations. This paper discusses the EPB operation of the eastern section of the Northolt Tunnel (NTE), which comprises two parallel 9.11-meter-diameter tunnels spanning 11 km. Tunnelling started in February 2024 and finished in June 2025.

## 1 PROJECT DESCRIPTION

### 1.1 *HS2 project and SCS JV project*


Figure 1. HS2 complete project overview
Source: Wikipedia

High Speed 2 (HS2) will be Britain's second purpose-built high-speed railway project after High Speed 1, which connects London to the Channel Tunnel. HS2 has been under construction since 2019.

The planned route runs from Handsacre in southern Staffordshire down to London, with a branch to Birmingham (see Figure 1).

The new high-speed track will directly serve London and Birmingham, while services to Glasgow, Liverpool, and Manchester will use a combination of the new high-speed track and the existing West Coast Main Line.

The SCS JV project comprises the 20.8 km southern end of HS2, connecting it to Euston Station in the heart of London.

## 1.2 *SCS JV stretch and details Northolt Tunnels East*

The SCS JV tunnels are divided into the Northolt Tunnels, which include Tunnels East (NTE) and West (NTW), and the Euston Tunnels. Details are shown in Figure 2. The 8.4-mile (13.5 km) Northolt Tunnel is being excavated with four Earth Pressure Balance (EPB) tunnel boring machines (TBMs). Two TBMs, *Caroline* and *Sushila*, were launched from West Ruislip to build the western part of the Northolt Tunnel (NTW), while *Anne* and *Emily* started from the Victoria Road site in North Acton to drive the eastern section (NTE). All four machines met at Green Park Way, where they were dismantled and removed via an extraction process shaft. High groundwater pressures and permeable ground conditions at the Green Park Way site required completing the TBM drives within a purpose-built pressurised steel reception chamber. The following sections of this paper detail the design, EPB construction methodology, and performance of the Northolt Tunnels East (NTE) section. The TBMs have been designed to handle the soft London Clay, the predominant geological layer in that section. Both TBMs have excavated an impressive 1,550,000 tonnes of London Clay and installed 5,840 concrete tunnel rings along the way. At peak performance, the TBMs advanced approximately 38 metres per day.

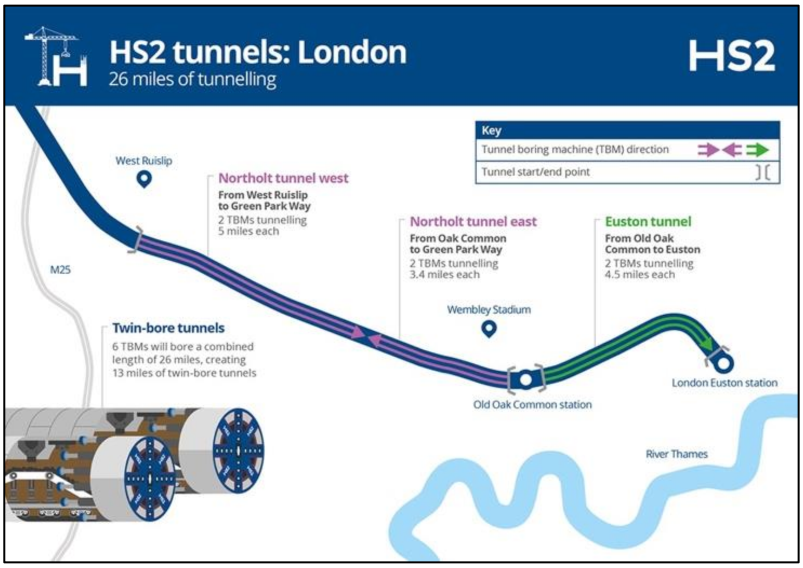

Figure 2. SCS section of HS2; Source: SCS JV

## 1.3 *Overview*

As shown in the geological long sections in Figure 3, the first 4.5 km of tunnel drive lies within the London Clay Formation (C, B, A3). The tunnel then enters the Harwich Formation, comprising the Upper Mottled Clay, Lower Mottled Clay, and Sand Units, with the invert marking the transition as the tunnel extends west of the London Basin and the London Clay thins.

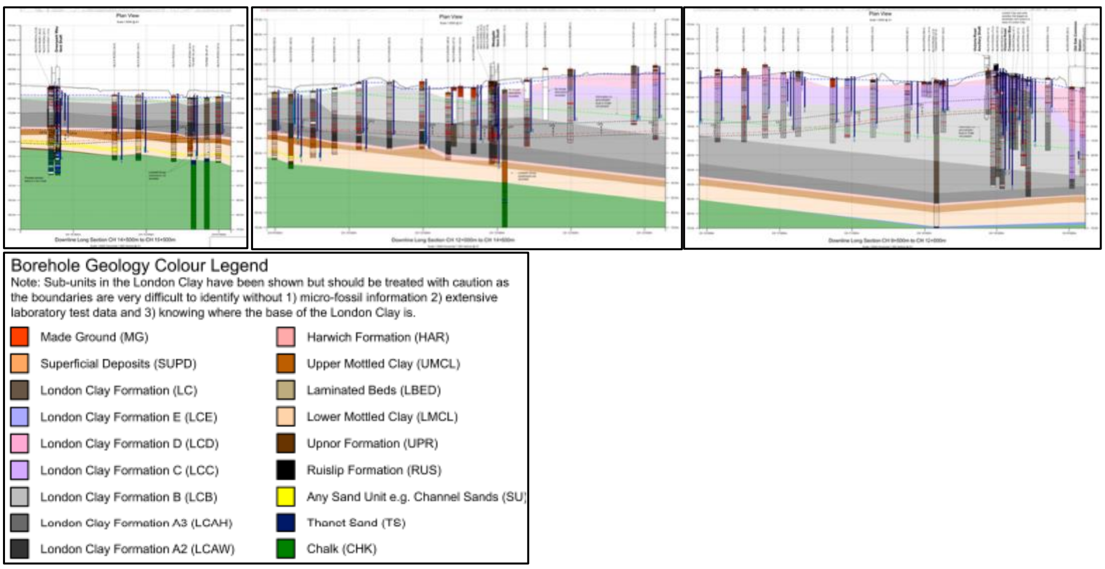

Figure 3. Geological overview of NTE tunnels; Source SCS JV

## 1.4 *London Clay Formations*

London Clay, a stiff, over-consolidated marine clay from the Eocene epoch, is a key geological formation in southeast England, characterised by high plasticity and low permeability. For tunnel boring machines, London Clay is challenging to work with because of its strong tendency to clog. Therefore, the clay must be converted into a plastic, flowable and compressible muck using foams and polymers, which also helps ensure the necessary face stability and reduces volume-loss settlements (Jancsecz, Langmaack, 1999).

# 2 TBM DESIGN

The TBM was designed and delivered by Herrenknecht based on the detailed specifications provided by SCS. During the design phase, lessons learned from completed bored tunnel operations in London Clay, as well as from other bored tunnels in comparable geologies, were incorporated.

## 2.1 *Cutterhead*

The cutterhead opening ratio was increased to approximately 58%, allowing an easier muck flow through the cutterhead into the excavation chamber. The cutterhead could switch between rippers and double-disk cutters. The detailed cutterhead configuration is shown in Figure 4.

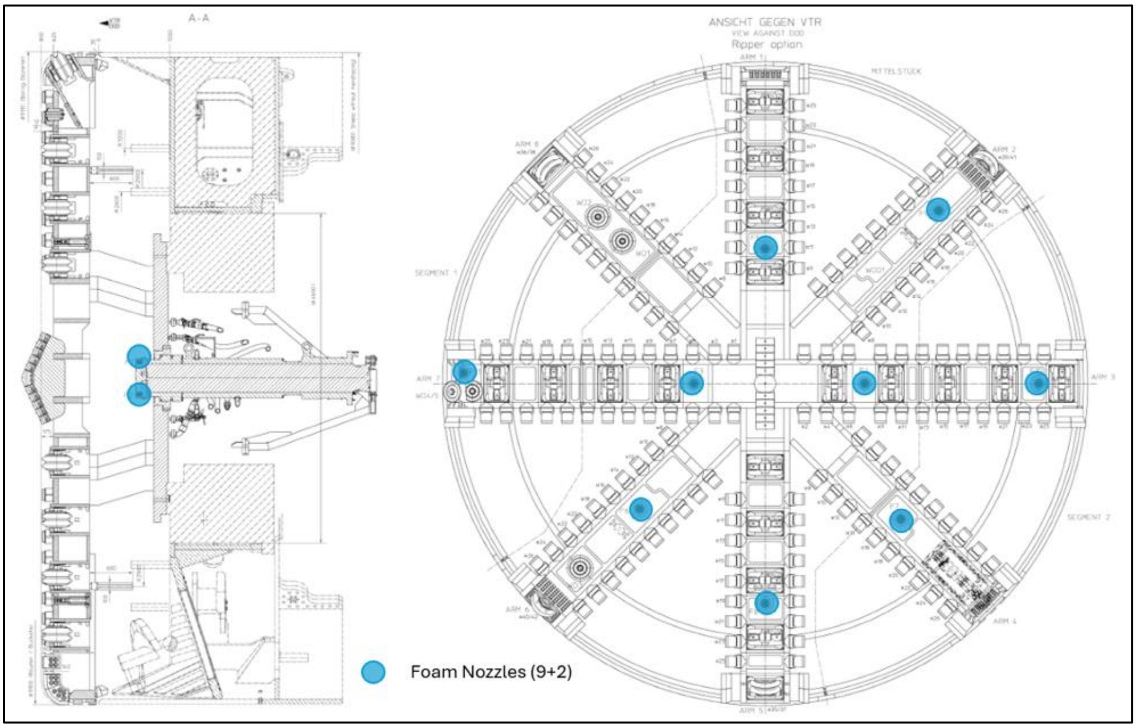

Figure 4. NTE cutterhead design, including foam conditioning nozzles (blue); Source: SCS JV

Apart from the opening ratio, the number and distribution of the foam nozzles are of utmost importance.

## 2.2 *Soil conditioning system*

In principle, the soil conditioning system follows industry-standard technology (see Figure 5). Nevertheless, a couple of new design features were implemented. The TBM was fitted with a rather important rotary coupling, providing sufficient independent feed lines to each injection nozzle at the cutterhead. These injection nozzles could be used for foam or water injection. The location and quantity of the foam nozzles (see Figure 4: Foam nozzles highlighted in blue) were specifically designed to deliver sufficient volumes of foam and water and distribute them most effectively. There is a total of 9 soil conditioning nozzles at the cutterhead and 2 additional nozzles in the centre of the excavation chamber.

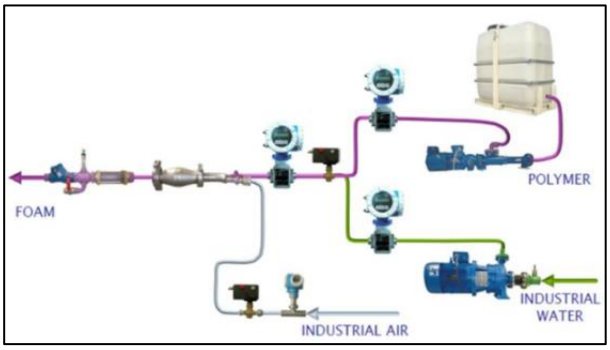


Figure 5. Foam Injection System; Source: Herrenknecht

# 3 LABORATORY SOIL TESTING

The London Clay, analysed at the MC laboratories as part of the soil conditioning research, was found to have the following characteristic values:

- Moisture content of received sample [%] 24
- Natural moisture content [%] as per GBR 29
- Atterberg plastic limit $w_P$ [%] 28
- Atterberg liquid limit $w_L$ [%] 71
- Atterberg plasticity index $I_P$ 43

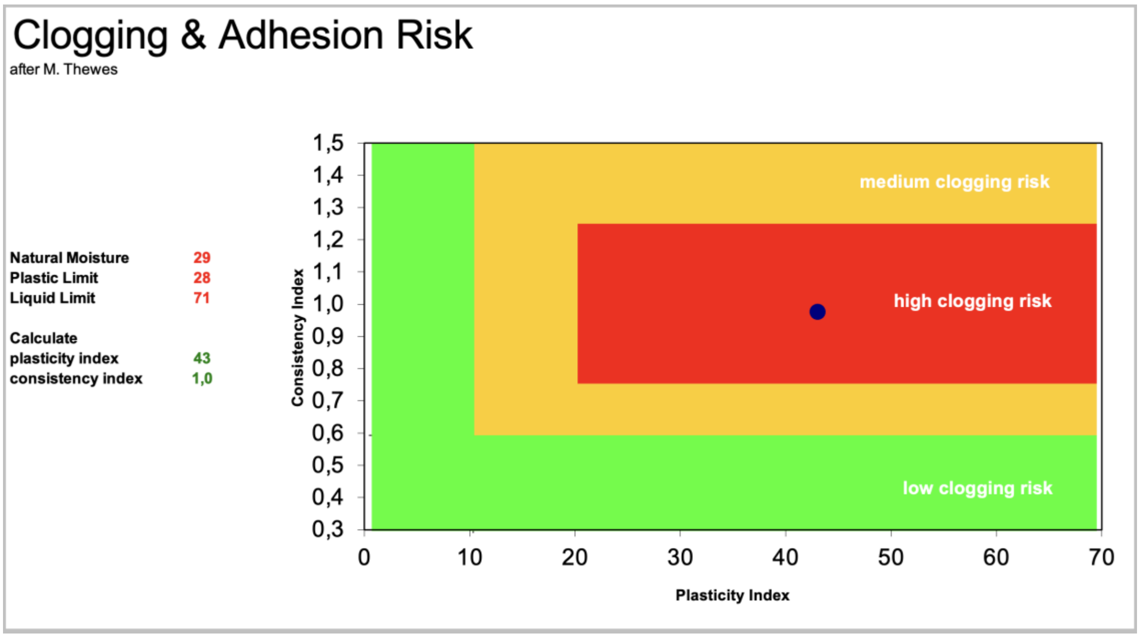


Figure 6. Clogging risk diagram (Hollmann Thewes 2013) with London Clay parameters (blue dot)

Inputting the determined London Clay plasticity and consistency values into the clogging risk diagram of Hollmann Thewes (see Figure 6) indicates, as expected, a very high clogging risk for the TBM. Therefore, key aspects of the SCS JV involved identifying suitable soil-conditioning products and the best possible starting parameters, which were later fine-tuned on site during TBM advance. A snapshot of the soil-conditioning tests is shown in Figure 7.

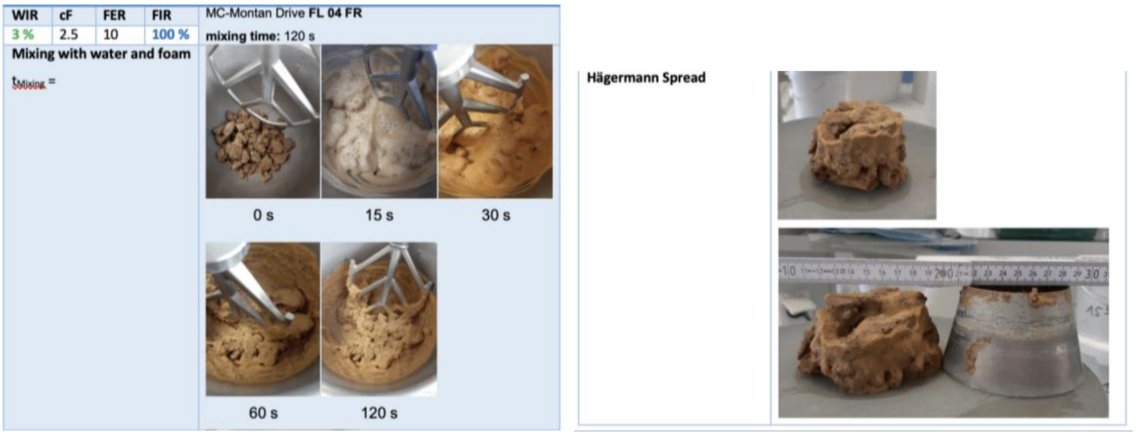

Figure 7. MC Laboratory soil conditioning example for London Clay; Source: MC-Bauchemie

The tests demonstrate the evolution of soil conditioning over time, including its rheological behaviour and the clogging effects of the conditioned soil on the mixing equipment and the bowl surface. The example presented demonstrates effective clogging protection and suitable rheological behaviour, even when slightly over-foaming.

The final MC soil conditioning proposal for full chamber EPB tunnelling through Lower Mottled Clay and London Clay is based on the soil conditioning tests performed:

| | |
|---|---|
| Foam type: | MC-Montan Drive FL 04 |
| $c_F$ | 2.5 to 3 % |
| FER | 10 (atmospheric) |
| FIR | 70-80 |
| WIR | 3-5 % |

This will result in approximately 200-260 kg of soil conditioner consumption per ring in closed EPB mode. In semi-closed mode, soil conditioner consumption is expected to decrease by around 30% compared with closed mode.

## 4 TBM ADVANCE IN LONDON CLAY

### 4.1 *TBM driving in semi-closed mode through full-face London Clay*

Due to the competency and stability of the London Clay, the TBMs could largely be operated in semi-closed mode, with a working chamber fill grade of around 70% and a compressed air bubble on top. Figure 9 shows a typical TBM parameter sheet for these sections, used alongside the permit to excavate. As shown by the volume loss calculations in Figure 8, all results were within the expected design limit of less than 1.0%, with no significant settlements. Most of this tunnelling stretch also has an overhead rail line and extensive rail-track monitoring.

| Volume Loss Back Calculations | | |
|---|---|---|
| Transect | Volume Loss % (DL Pass) | Volume Loss (%) (UL Pass) |
| Cemetery Transect 1 | 0.69% | 0.54% |
| Cemetery Transect 2 | 0.32% | N/A |
| Cemetery Transect 3 | 0.45% | 0.12% |
| Transect 66C | -0.12% | -0.07% |
| Transect 66B | -0.01% | -0.08% |
| Transect 66A | 0.23% | 0.20% |
| Transect 66 | 0.15% | 0.12% |
| Transect 65 | 0.30% | 0.16% |
| Transect 64A | 0.19% | 0.24% |
| Transect 64 | 0.34% | 0.25% |
| Transect 63 | 0.28% | 0.03% |
| Transect 62A | 0.27% | 0.01% |
| Transect 62 | 0.07% | 0.06% |
| Transect 61 | 0.39% | 0.35% |
| Transect 60A | 0.36% | 0.13% |
| Transect 60 | 0.13% | 0.43% |
| Transect 59 | 0.28% | 0.58% |

Figure 8. Volume loss back-calculation @ air pressure mode; Source: SCS JV

| | | | | | |
|---|---|---|---|---|---|
| Max Thrust Force | 23000 kN | | Max Torque | 5500 kNm | |
| Max Speed | 55.0 mm/min | | max. rpm cutter head | 4.0 rpm/min | |
| Max Penetration | 30.0 mm/rpm | | Max. Contact Force | 15000 kN | |
| Backfill Grouting | | | | | |
| Grout Volume (Theorotical) (m3/ Ring) | 8.81 m3 | | Component B (%) | 7.6% | |
| Grout Pressures | MAX | MIN | | MAX | MIN |
| Pressures (Sensor 1 & 7) | 3.5 bar | 1.0 bar | Pressures (Sensor 3 & 4) | 4.3 bar | 1.8 bar |
| Pressures (Sensor 2) | 4.0 bar | 1.5 bar | | | |
| Pressures (Sensor 6) | 3.8 bar | 1.3 bar | 2ndary Grouting Pressure | 3.0 bar | 0.5 bar |
| Soil Conditioning | | | | | |
| Foam Expansion Ratio | 4 to 5 % | | Polymer Expansion Ratio | N/A | Comments |
| Foam Injection Ratio | 50 to 60 l/mm | | Polymer Injection Ratio | N/A | Foam Type : FL04 |
| Foam Concentration | 2.0% | | Polymer concentration Ratio | N/A | |
| Free Water | 250 to 300 l/min (F5 & F8) | | Bentonite | N/A | |
| Segmental Lining Support Class (Type) | Ring 631 - 868: Type II (except CP03) CP03 Ring 735 - 741 | | | | |
| Spoil Management | Spoil Target Weight | 235.8 ton | | Spoil Target Volume | 124.1 m3 |
| | Theoretical Density | 1.9 m3 | | Moisture content | N/A |
| Earth Pressure (Crown Pressure sensors) (Bar) | Target | Min. | | Max. | |
| | 0.5 bar | 0.0 bar | | 1.0 bar | |

Figure 9. Typical TBM parameter sheet @ air pressure mode; Source: SCS JV

## 4.2 *Changing TBM driving mode from semi-closed to full EPB pressure*

During some of the most critical and settlement sensitive sections of the alignment, SCS JV operated the machines in full EPB mode under full-face London Clay conditions. This was particularly the case while mining within the Brent Valley Sewers' (BVS) zone of influence, with

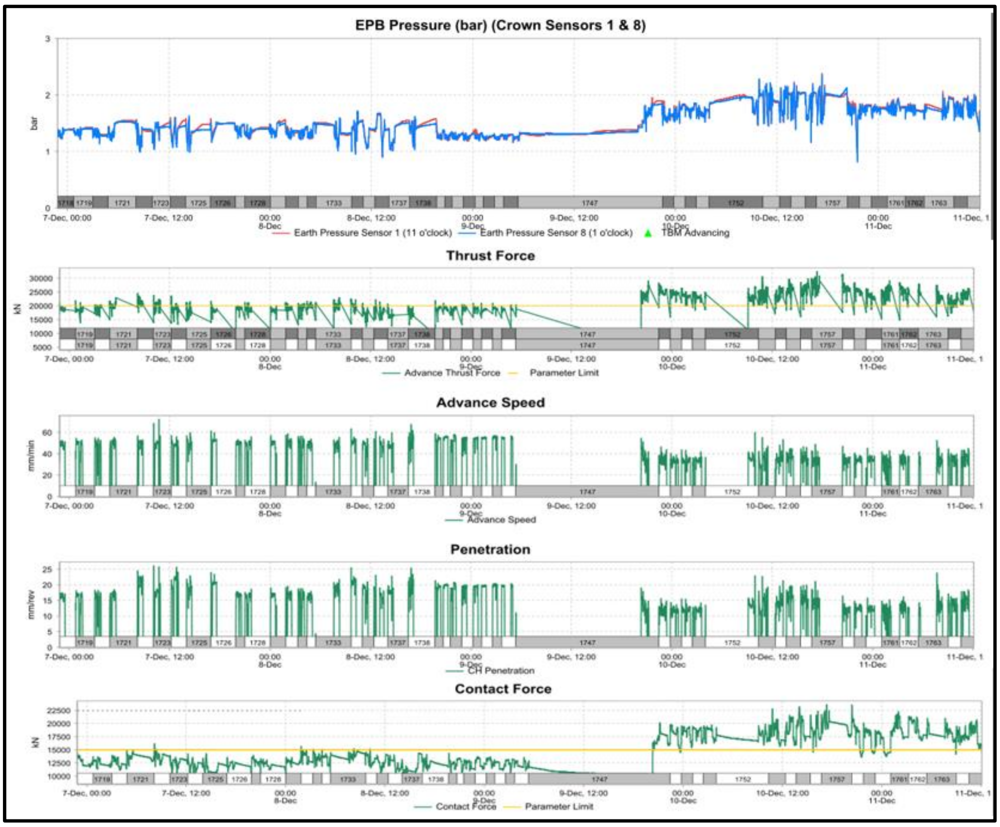


Figure 10 TBM driving parameter change from semi-closed to full EPB mode; Source: SCS JV

a design face pressure of 1.8-2.0 bar in the top crown section. The machines mined at a distance of 1.5 TBM diameters below the BVS, which was considered the most sensitive asset encountered along the alignment. The BVS is a 2.7m inner-diameter main sewer trunk connecting a population of approximately 425,000 people to the Mogden Wastewater treatment plant.

As the TBM approached the sewer, the driving mode (as illustrated in Figure 10) was switched from December 9th to December 10th 2024: from semi-closed mode with around 70% chamber filling and top crown pressures of 0.8-1.0 bar to full EPB mode with 100% chamber filling and top crown pressures of 1.8-2.0 bar EPB pressure. The selected TBM speed during semi-closed mode operation was 50 mm/min, while in full EPB mode it was voluntarily reduced to 30-40 mm/min. Contact and thrust forces changed significantly in full EPB mode, but, due to the well-defined use of foam and polymer, always remained within very reasonable ranges (see Figure 10).

As an additional measure to limit settlements, the annulus around the TBM shield was stabilised with bentonite suspension and topped up using the TBM's onboard pressure-controlled bentonite feeding system.

With this configuration, both NTE TBMS passed through the Brent Valley Sewer without damage and with only minimal settlements, as illustrated by the volume loss calculations (Figure 11and the settlement data (Figure Figure 12): the allowed settlement in mm is shown as the black curve, and the measured settlements after the passage of both TBMs are shown as the red dotted curve. The individual settlement curves for each TBM have been re-calculated as the orange curve for the 1st TBM (Downline) passage and the green curve for the 2nd TBM (Upline).

| Transect | Volume Loss % (DL Pass) | Volume Loss (%) (UL Pass) |
|---|---|---|
| Transect 53 East [Alperton Lane ] | 0.65% | 0.12% |
| Transect 53 West [Alperton Lane ] | 0.62% | 0.13% |
| Transect 52A (BVS) | 0.64% | 0.27% *(limited I&M coverage)* |
| Transect 52A (DL & UL Combined) | 0.33% *(limited I&M coverage above UL)* | |
| Transect 52 (Pipetrack) | 0.38% | 0.19% |
| Transect 52 (DL & UL Combined) | 0.26% | |
| Transect 51 | 0.55% | 0.80% |
| Transect 50 | 0.77% | 0.56% |

Figure 11. Volume loss back-calculations for EPB mode; Source: SCS JV

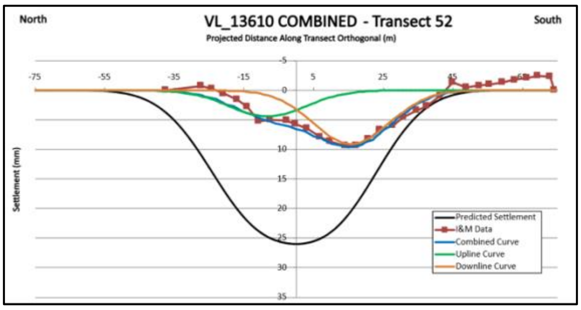


Figure 12. Settlement data for NTE Upline and Downline tunnels; Source: SCS JV

### 4.3 *Foam consumption in full EPB mode*

The laboratory soil-conditioning trials indicated a consumption of 200-260 kg of foam concentrate per ring in full EPB mode. The TBM data recorded over the entire stretch of full EPB advance showed a minimum foam consumption of around 165 kg per ring, with medium consumption rates ranging from 190 kg to 250 kg. The laboratory consumption data demonstrated a high level of accuracy and were validated under actual site conditions.

## 5 INNOVATION: AFCS – ASSISTED FOAM CONDITIONING SYSTEM

AFCS is a joint development by MC-Bauchemie, TPC Tunnelsoft, and SCS, aimed at enhancing safety and comfort during EPB tunnelling. AFCS is designed to assist TBM operators by providing a quick overview and improving security by reducing the interpretation required for existing parameters. It also aims to facilitate full EPB driving mode with minimal settlements and has been extensively used to train TBM operators for proper EPB mode tunnelling after long semi-closed sections. AFCS can also predict clogging risks, allowing the TBM operator to make early adjustments before irreversible clogging occurs.

The display is divided into four main sections, providing graphical feedback on the foam injection port status and showing selected KPIs related to the overall TBM condition and soil conditioning status. Thresholds are set based on the TBM design, soil-conditioning test results, muck disposal frame conditions, and the developer's experience.

### 5.1.1 *AFCS @ Ringbuild mode*

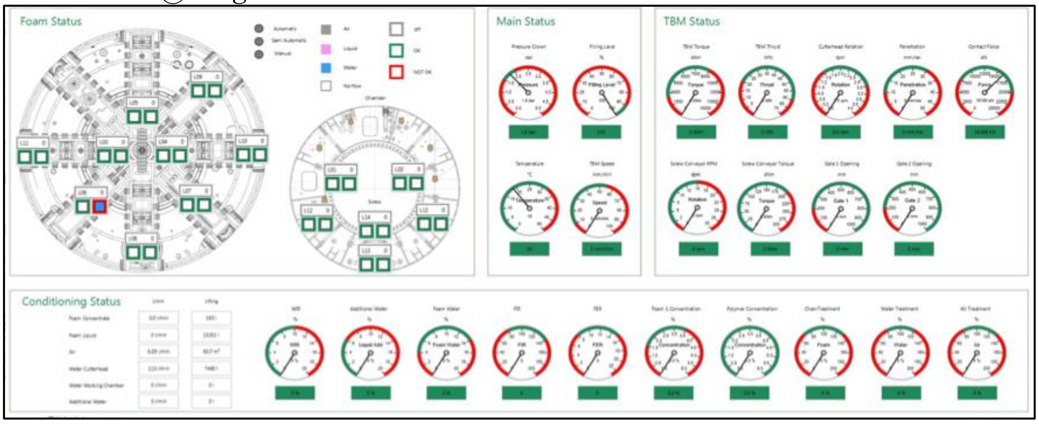


Figure 13. AFCS screen during ringbuild; Source: TPC

During ring construction in full EPB mode, it is crucial – among other KPIs – that both excavation screw gates are closed and that the EPB pressure remains at the designed level with a fully filled working chamber. Figure 13 shows all relevant indicators in green, indicating that everything is in order in this respect.

Furthermore, no foam or water must be injected unintentionally at the cutterhead or into the working chamber; the soil conditioning system should be turned off. Figure 13top-left section of Figure 13 shows one injection port indicator at the cutterhead in red, signalling water injection (>100 litres per minute or more than 3 m³ during ring build), which severely disrupts soil conditioning and would likely not have been detected without AFCS. The cause was a blocked automatic valve that failed to close properly.

### 5.1.2 *AFCS @ Advance mode*

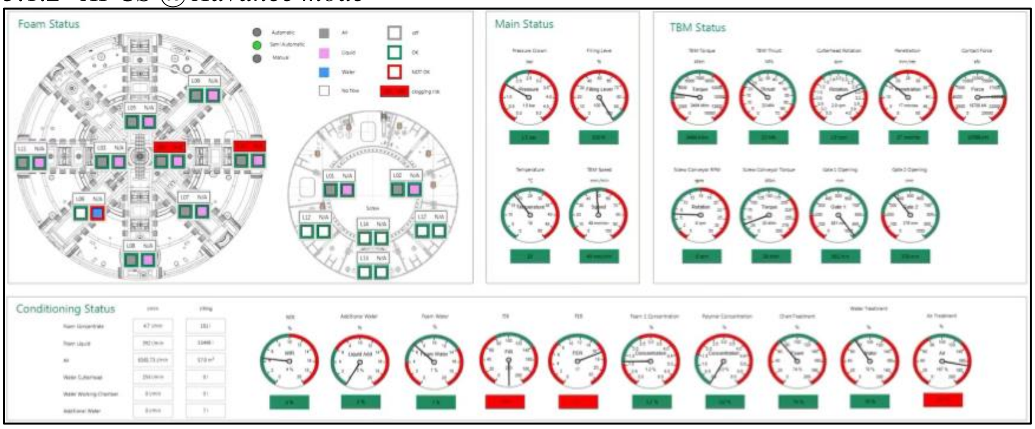


Figure 14. AFCS screen during EPB driving operation; Source: TPC

An example of an on-site situation during TBM advance in full EPB mode is shown in Figure 14. The operator's performance is generally satisfactory; however, the current driving approach carries a risk of clogging, as indicated by the red-highlighted areas in the top-left cutterhead graphical section. These early disturbances are still reversible, allowing the operator to adjust soil conditioning and driving parameters to reduce the risk of clogging. The Assisted Foam Control System (AFCS) therefore highlights relevant key performance indicators (KPIs) in red.

Timely adjustments to operating parameters can prevent severe cutterhead clogging, a condition that is usually irreversible and requires subsequent manual cleaning, causing operational delays and safety concerns.

## 6 SUMMARY AND OUTLOOK

Both semi-closed and full EPB mode tunnelling delivered highly secure results with only minimal settlements, even allowing crossings under sensitive infrastructure.
Adapting both the cutterhead design and soil conditioning system, based on lessons learned from previous projects in similar geology, proved effective and was a key factor in the successful tunnel drive. The positioning of the foam ports on the cutterhead, together with the flexibility of the soil conditioning system to add water in a controlled manner directly in front of the cutterhead as a standard feature integrated into the soil conditioning PLC system, clearly demonstrates the importance of this configuration for effective soil conditioning.
AFCS significantly helped manage the soil-conditioning operation, especially during passage under settlement-sensitive assets. The clogging preview feature proved successful in initiating fine-tuning of soil conditioning, enabling control of surface settlements and minimising the impact of clogging on TBM drive operations.
Downtime caused by clogged or blocked cutterheads was minimised.

These improvements in TBM design and soil-conditioning efficiency are evident when comparing cutterhead breakthrough photos from earlier projects:

Figure 15. CTRL II; own source

Figure 16. Northern Line Extension Source NLE JV

Figure 17. HS2 SCS NTE; Source SCS JV

Figure 15 shows one of the CTRL II projects in London Clay from 2001-2003, with a clogged cutterhead, while Figure 16 depicts the Northern Line Extension project in London Clay from 2017-2018, where the large openings between the arms were kept clear. However, clay still built up on steel surfaces, reducing cutterhead efficiency and still causing surface and centre clogging. In contrast, Figure 17 shows the HS2 NTE TBM breakthrough cutterhead condition from June 2025, with all openings, including those in the centre, remaining clean. All injection ports on the cutterhead remained operational throughout mining, with none ever lost.

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