SEQUENTIAL EXCAVATION METHOD TUNNELLING IN WEAK SANDSTONE USING INNOVATIVE METHODS

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ABSTRACT: The A3 Hindhead road improvement scheme in Surrey, UK includes 1.8km of twin bore tunnels excavated using the sequential excavation method. This paper describes the design and construction of the tunnels, focusing on the management of risk during construction. Two categories of construction risk are identified: construction project risk and health and safety risk. Systems have been put in place at A3 Hindhead to deal with both of these types of risk and the systems are described. The paper concludes by listing the principle factors in making the project a success, including personnel and design matters.

1. INTRODUCTION

The A3 Hindhead Project, in Surrey UK, is a 6.7km dual carriageway trunk road including two 1.8km twin lane tunnels. The scheme is being delivered on behalf of the UK Department of Transport under a Highways Agency Early Contractor Involvement (ECI) contract by Balfour Beatty with Mott MacDonald employed as Tunnel Designer by Balfour Beatty. The tunnels were constructed using the sequential excavation method (SEM) and when completed in July 2011 will complete the dual carriageway link between London and Portsmouth.

The tunnels incorporate a 7.3m wide carriageway with a 5.03m high traffic gauge and 1.2m wide verges on either side. Ground support comprises a 200mm thick sprayed concrete permanent primary lining. A secondary lining of; cast in-situ sidewalls typically 340mm thick and, sprayed concrete secondary crown lining of 150mm thickness was designed to support hydrostatic loading and internal M&E fixtures only (see figure 1). Interconnecting cross passages are located at nominal 100m centres principally to facilitate movement of pedestrians between tunnels in case of emergency. Emergency niches are provided midway between cross passages to provide a communications refuge for passengers in difficulty, connecting directly with the tunnel authorities.

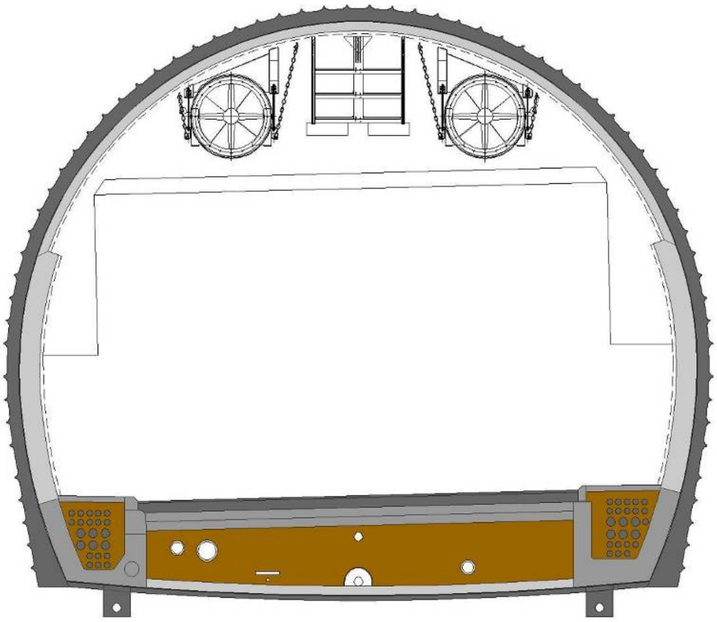

Figure 1: Tunnel General Arrangement

The tunnels are located in the Hythe Beds, within the Lower Greensand Series formation, a variable sequence of interbedded sands and sandstones. At its southern end the tunnel passes through medium dense silty clayey fine to medium sand, with subordinate weak to strong sandstone and chert bands which required canopy tube support. Tunnel construction included a number of advanced technologies:

- Use of steel or macro-synthetic fibre reinforcement in the permanent load bearing primary lining.
- Use of remote controlled robotic spraying for primary lining, sprayed waterproof membrane application and sprayed concrete crown secondary lining, giving improved safety and increased production rates.
- Use of total station for reflector-less surveying allowed fast accurate surveying and the omission of lattice girders whilst maintaining a good tunnel profile.
- Use of spray – applied waterproofing system.
- Use of micro-synthetic fibres in sprayed concrete for the secondary lining crown.

The paper describes the actual achievements on site with regard to; a) construction progress actual and planned, b) actual support type employed compared with envisaged, c) the management on site of tunnel construction risk, d) the observed ground movements as monitored and predicted, e) the materials employed and the site trials employed to prove the materials, f) significant innovations introduced, g) lessons learned and cautionary tales.

2. DESIGN

A site specific stratigraphy was developed which subdivided the Hythe Beds by their different material properties. At its southern end the tunnel passes through the soil dominated strata comprising medium dense silty clayey fine to medium sand, with subordinate weak to strong sandstone and chert bands. The majority of the tunnels were preferentially located in the rock dominated strata comprising weak sandstone with subordinate horizons of fine to medium sand.

Six support types, later expanded on site to seven, and eight support contingency measures were envisaged at the design stage; these are listed in Tables 1 and 2.

Support Type	**Tunneling Medium**	**Description**
1	Rock dominated strata.	1-2m heading advance. 2m bench advance > 25m behind heading.
2	Combination of soil and rock dominated strata.	12m long canopy tubes installed every 8m advance. 1m heading advance. 2m bench advance > 25m behind heading.
3	Combination of soil and rock dominated strata.	12m long canopy tubes installed every 8m advance. 1m heading advance. 2m bench advance 2m behind heading.
4	Soil dominated strata with low cover.	12m long canopy tubes installed every 8m advance. 1m heading advance. 2m bench advance 2m behind heading. 2m full closed invert advance 2m behind bench.
5	Rock dominated strata with low cover.	12m long canopy tubes installed every 8m advance. 1m heading advance. 2m bench advance > 25m behind heading.
6	Combination of soil and rock dominated strata.	12m long canopy tubes installed every 8m advance. 1m heading advance with lattice girders. Bench advance as per Types 2-4 (dependant on location).
7	Soil dominated strata.	12m long canopy tubes installed every 8m advance. 1m full closed heading advance. Bench advance as per Types 2-4 (dependant on chainage).

Table 1

Type	**Additional Support Measures**
Canopy Support	Canopy tubes
	Spiles
Face Support	Inclined face
	Sealing layer
	Face support wedge
	Face Dowels
Structural Invert	Compression invert strut
	Domed invert strut

Table 2

The primary lining at Hindhead was designed to carry the residual permanent ground load once arching has taken place within the ground. The lining was 200mm thick steel or macro-synthetic fibre reinforced sprayed concrete and the advance rate was linked to the strength gain of the concrete to ensure that the lining had sufficient strength as the tunnel advanced and the acting ground load increased. Flexural strength gain from the addition of structural fibres was not taken into account when designing the lining; the concrete was designed as plain concrete.

Testing of various parameters was required prior to installation. The requirement for early age strength gain was compliant with the Austrian J2 curve (this equates to 0.5 – 1.5MPa at 1 hour) and C32/40 28day strength. Testing of sprayed concrete was carried out onsite over the winter of 2007/08 in low ambient temperatures to assess cement and accelerator performance. The temperature during tunnelling remained above 20ºC at all times and whilst the early age strength requirements proved difficult to obtain during testing, they were achieved daily during tunnelling. The 28day strength was achieved reliably both during testing and tunnelling.

A minimum energy absorption of 700J using the EFNARC panel test was also required. This was achieved by varying the quantity of fibres added to the mix. The lining was sprayed using 30kg/m^3 of steel or 6kg/m^3 of polypropylene structural fibres. Durability of the lining was assured through testing of water penetration and drying shrinkage. The samples were tested in accordance with BS EN12390-8 with water penetration requirement less than 50mm and drying shrinkage less than 0.03% in accordance with ASTM C157. Admixtures to control pumpability and retardation of the mix were added prior to testing so that the complete mix was tested. The ability to treat the primary lining as the permanent structural lining was achieved by providing a 'sacrificial' secondary lining. The secondary lining was fire hardened using micro-fine polypropylene fibres added at the rate of 1kg/m^3. This dosage was checked in laboratory fire tests on the full lining thickness subject to the hydrocarbon time temperature curve, for a duration of 120 minutes, given in BS EN 1991-1-2:2002 Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire, British Standards Institution, (November 2002).

3. RISK MANAGEMENT

This section will consider two categories of risk: construction project risk and health and safety risk. Construction project risks are those construction risks which have the potential to cause overruns and delay to the project as a whole. Health and safety risks relate to hazards with the potential to adversely impact personnel involved in the construction of the tunnel and members of the public who may be affected by the works.

Management of the construction project risk was achieved through Daily Review Meetings (DRMs) attended by competent and experienced personnel charged with selecting the most appropriate course of construction action going forward. The purpose of the DRM was to check the performance of the constructed tunnel against real time data collected during the previous 24 hrs and trend data. The DRM process is shown schematically in Figure 2. The requirement to hold DRMs was written into the contract specification. Data reviewed included: tunnel settlement and convergence, surface settlement, geological face logs, probing records, early age and 7 & 28 day sprayed concrete strength and quality, environmental monitoring and tunnel inspections.

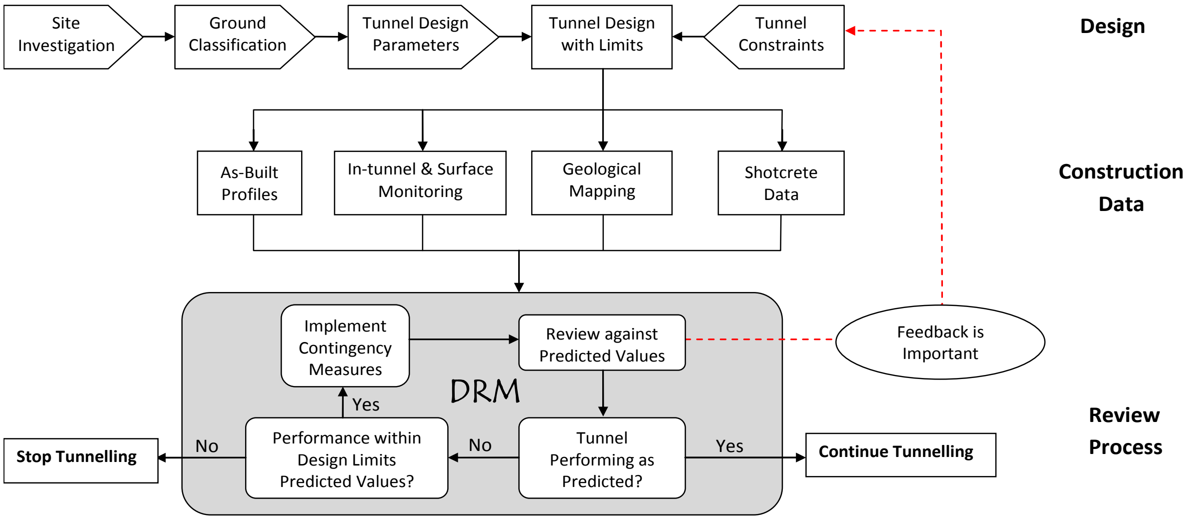

Figure 2 – DRM process map

The product of the DRM was the Required Excavation and Support Sheet (RESS). A RESS was produced daily for each face and was effectively a ‘permit to dig’ (i.e. no excavation was permitted without a valid RESS). Each RESS was signed at the DRM by the Contractor, Designer and an Independent Engineer (as requested by the Contractor to ensure impartiality). This procedure ensured that the contract parties carried out a daily review of the real time data to confirm that the chosen lining type and additional measures adopted were performing correctly and were compatible with current and expected ground conditions.

The risk of injury to personnel within the tunnel was mitigated principally by the combination of; good in tunnel ventilation and lighting leading to clear visibility, mechanised excavation, spoil removal by conveyor, avoidance of the use of lattice girders or reinforcing mesh and, remote application of sprayed concrete by robots. These methods removed many of the safety hazards of open face excavation and in particular avoided the need to work beneath unsupported ground. Access requirements were set such that personnel should never be required access beneath in place sprayed concrete with a UCS of less than 1MPa. The required geological face inspections, which did require close inspection of and access to the face, were therefore carried out from within a protected cage. The presence of faults, causing poor face stability, prevented close to the face inspections required to determine the size of the elephant feet support. This resulted in: a larger universally applicable elephant foot, an inclined face excavation and a 3m personnel exclusion zone at the face. The inherent strength gain requirements ensured that the lining outside the exclusion zone had achieved an adequate and safe strength.

Figure 3 – Primary Lining Application

The impact of tunnelling works on the public was minimised by the inclusion of additional measures when tunnelling beneath third party structures. Over the 1.8 km length of the tunnel route there were relatively few surface constraints as most of the route was below heath land. There were two crossings of the A3 and one of the A287; the tunnel also passed directly beneath a line of houses. The first road crossing was carried out using reduced advance length and continuous spiling with close monitoring but these additional measures were relaxed at subsequent crossings. The buildings were monitored to observe any movement associated with tunnelling.

Through careful application of the risk mitigation measures discussed, tunnel construction has been completed ahead of programme and without significant incident. A high quality finished product has been delivered despite the challenging ground conditions.

4. RISK MITIGATION DURING CONSTRUCTION

Cross passage construction was sequenced in consultation with Surrey Fire and Rescue to ensure that adequate Emergency Services access was available during construction through maintaining the trailing tunnel close behind the leading tunnel and constructing interconnecting cross passages within 230m of the face.

Tunnelling began at the north portal. Type 5 support (including canopy tubes) was installed for the first 40m in the southbound and 20m in the northbound tunnels to address low ground cover and faulting. Face dowels proved ineffective in this material and were discontinued. Invert struts were required at the portal entrances due to poor ground encountered at the start of tunnelling. Once beyond the faulted material, Type 1 support was the main excavation type with additional support measures incorporated where required.

The heading advance length of Type 1 support was varied from 0.75m to 1.5m depending on ground conditions. The limit for advance was set at the DRM along with any mandatory additional measures. The experienced tunnel team at the face (including geologists, miners, engineers and surveyors) were able to vary the advance length and support level down to the limit specified in the DRM. The tunnel team could never install less support than that specified on a RESS (but they could always install more). The design specified full face excavation everywhere although the contractor elected to use partial face excavation where judged of benefit by the tunnel team.

4m long GRP spiles were installed at locations of poor ground with open joints, faulting and areas of predicted overbreak. From the many spiling contingency measure options, pre-drilled 32mm solid GRP spiles were widely used and placed in grouted holes in both full arrays and at discrete locations around the tunnel profile. GRP was selected for the spiles to ensure lining durability was maintained. Minimum spiling requirements were specified at the DRMs (e.g. when tunnelling beneath the A3) but additional spiling was specified where required by the tunnel team. A total of 26% of the tunnel required canopy support (canopy tubes or spiles) compared with the initially anticipated 39%.

Figure 4 –Typical Spile Installation

The prediction of ground conditions ahead of the face relied on a combination of monitoring changes in the face and crown during excavation; the use of probe holes, borehole data and a detailed knowledge of the stratigraphic and structural geological conditions. Identification of changes in the condition of the face and crown during excavation alone could have lead to support being installed later than required as the condition of the face often changed rapidly when approaching a fault. This was particularly true where the fault was sub-parallel to the orientation of the tunnel face. The effectiveness of spiles relied on them being fully embedded in the shotcrete arch as if not fully embedded some of the restraint provided by the arch is lost.

From the south portal the tunnels descended through the UHB/C beds with a high percentage of sand and very weak sandstone requiring support ahead of the face excavation. An additional support type support (Type 7) was developed during construction for this ground location. Type 7 support provided a closed-heading support system where a structural invert was installed in the heading. This allowed the heading to be progressed safely in the sand-dominated material, giving programme savings and safety benefits to the Contractor. Grouting was used initially in conjunction with canopy tubes, however, the grout escaped through the fissures and locally wetted and weakened the sands around the tubes and it was concluded that the canopy tubes alone provided best support.

Figure 5 –Typical Canopy Tube Installation

Monitoring was carried out by dedicated personnel using a total station which allowed readings from both retro targets and reflector-less survey points around the tunnel. Reflector-less readings established base values in the crown immediately the shotcrete had been sprayed. Three point arrays were used in the heading excavation with an additional two points added during bench construction. Arrays were generally installed every 20m along the tunnels with readings taken daily. Closer spacing with more frequent readings were taken in areas of poor ground or when lining modifications were initialised. 3D coordinates of all monitoring points were recorded and a programme devised to provide a graphical representation of any changes in settlement and convergence each having their own trigger limits.

Initial monitoring indicated that convergence was generally within the expected 8mm green trigger limit. Settlement readings were however found to be quite variable and occasionally reached the initial Amber and Red trigger limits. This was judged to be largely due to difficulty in cleaning the elephant foot foundation and was alleviated by changes to the elephant foot design, increase in size, and the use of grading buckets to ensure a clean formation and these measures ensured compliance with the revised 25mm green trigger limit.

Surface settlement arrays were installed across the line of the tunnels at the portals, the road crossings and around the houses. The surface arrays were positioned to confirm that settlement was within the predicted 1% face loss prior to the tunnels passing beneath the houses and the A287. Actual recorded face loss at this location was around 0.5% resulting in a maximum surface settlement of approx 12mm. This was within the limit prescribed by a utility provider to protect an 8-inch diameter CI gas main buried below the A287. Building damage was confined to fine plaster cracks of decorative nature only.

5. CONCLUSIONS

Tunnelling works began from the north portal on the 1st February 2008 during a visit by the Secretary of State for Transport. Both headings progressed well, achieving a maximum combined advance rate of 457m per month. Excavation from the south portal began on the 14th May 2008 but was significantly slower than from the north due to the more complex initial support requirements resulting from the poorer ground conditions.

Where poor ground was encountered at the northern end, tunnel progress typically halved as additional measures such as spiles were required. Simultaneous breakthrough of both headings from both ends was achieved at a celebration on the 26th February 2009.

Figure 6 – Tunnel Breakthrough, February 2009

Bench excavation began on the 9th July 2008 in the southbound tunnel. Advance lengths for the bench were fixed at 3m and the benches were excavated in several sections with multiple faces open at once. This helped to achieve a maximum advance rate of 1232m per month. Completion of all primary lining works was achieved on 31st March 2009, ahead of programme.

The risk mitigation strategy employed ensured that the primary lining was completed successfully and safely. A high quality finished product has been delivered despite the challenging ground conditions encountered. The principal contributory factors to this success included;

- Continuity of staff: by maintaining core staff through from design to construction, the limitations of the design were understood and the design intent followed onsite.
- Shared responsibility: by ensuring that representatives of all parties were present at DRMs, the selected support type and additional measures are agreed by all. The tunnel team (including geologists, miners, engineers and surveyors) were responsible for face-by-face decisions and represented both the Contractor and Designer.
- Flexible design: providing a design which was sufficient to cover all expected ground conditions but which could be minimised to provide efficient support when good

ground was encountered was vital to the success. Also a design where additional measures were discrete allowed them to be installed as and when required independent of other measures being installed at that time.

- Constant design review process: an onsite team of vigilant designers were able to constantly evaluate the design being installed and look for improvements where possible. These improvements brought safety and efficiency gains to the Contractor.