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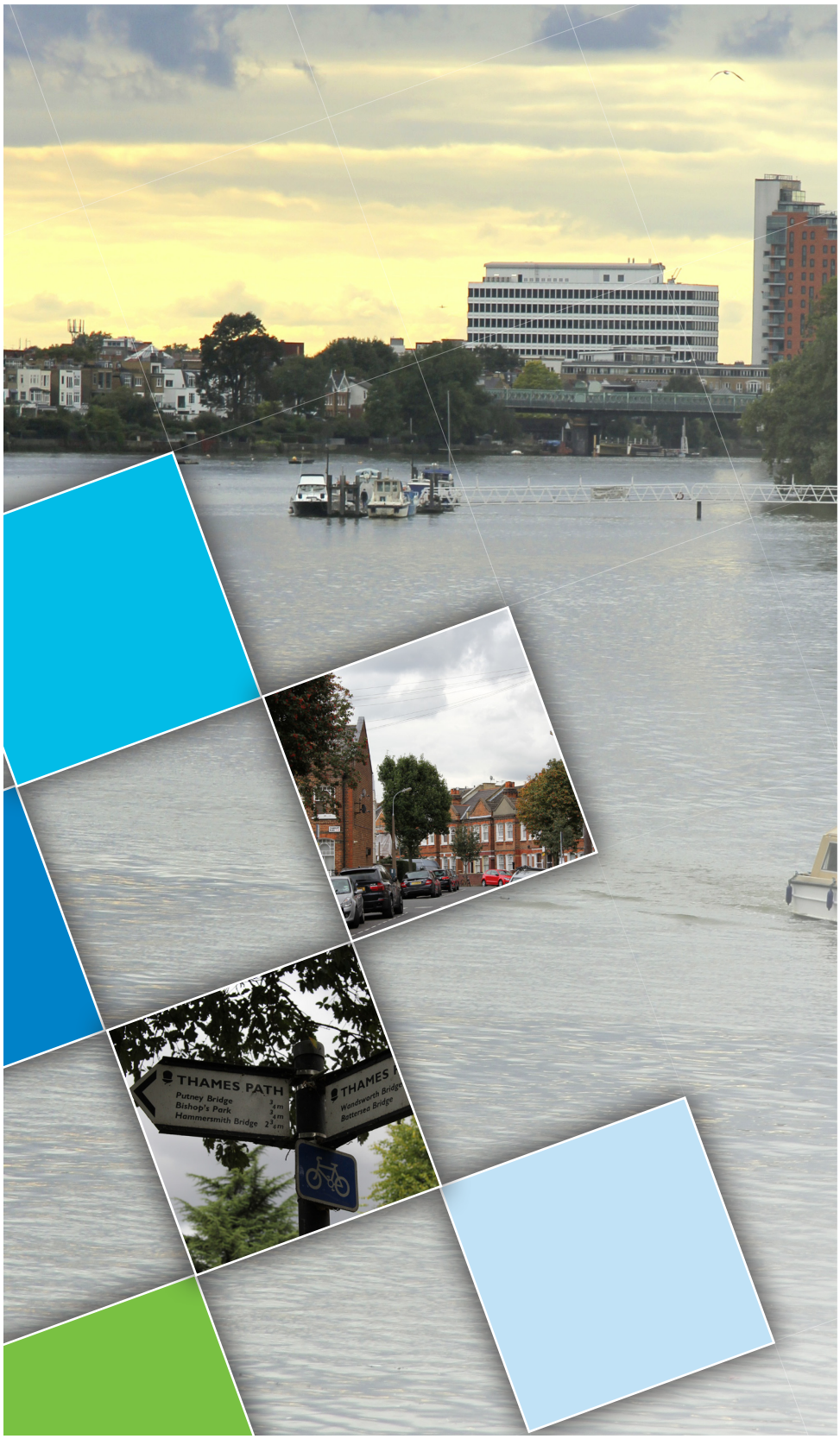
London Borough of Hammersmith and Fulham



Thames Tideway Tunnel – Benchmarking and Risk Assessment of Alternative Drive Strategies

November 2013

CDM Smith

Document Control Sheet

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Executive Summary

This document summarizes CDM Smith's expert review for the proposed Thames Tideway Tunnel (referred to as the "preferred scheme") and specifically evaluates two alternative drive strategies in response to the request by London Borough of Hammersmith and Fulham (LBHF). CDM Smith's approach to carrying out our review was to:

- Review available information on the planning, approaches and assumptions that have been taken by Thames Water related to the preferred scheme.
- Conduct a benchmarking study of the issues and or technical parameters considered most important for this project as related to the two alternative drive strategies.
- Identifying the major risk considerations of the issues and parameters under consideration of the two alternative drive strategies in comparison to the preferred scheme.
- Perform a risk evaluation for the items identified above specifically for two alternatives to the current planning of shaft location and spacing with regards to tunnel drive length for the proposed Thames Tidewater Tunnel project.
- Prepare this report and provide expert consulting before and possibly during the scheduled public meetings.

Two alternative drive strategies were proposed by LBHF. Both alternatives were assessed using the approach as outlined above. The results of both assessments are presented in the below sections.

ES - 1 Alternative A - Alternative Drive Strategy excluding Carnwath Road drive site

Alternative A is defined as follows;

Alternative A: Alternative Drive Strategy excluding Carnwath Road drive site - this alternative follows the current Thames Tideway Tunnel alignment but excludes the drive shaft and long term ventilation facility at Carnwath Road. In this alternative, active ventilation facilities are proposed at either end of the Thames Tideway Tunnel - at Acton Storm Tanks, and at Abbey Mills Pumping Station (with the remainder of the existing TTT Air Management Plan (Thames Water, 2013) unaffected). This alternative results in a single 12km drive from between Acton Storm Tanks and Kirtling Street at 7200m ID using, as in the preferred scheme, an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM).This alternative is presented in Figure ES-1.

Figure ES -1: Alternative Drive Strategy - Alternative A Overview Sketch

Based on our research of both public documents and in-house projects and interviews with TBM manufacturers, our basic conclusion is that the extended tunnel drive length to a total of 11.95 km is technically feasible and has been achieved successfully. There are some added risks to the project that have been identified in this study concerning tool wear and ventilation as they are affected by the longer tunnel drive. These risks can be managed and mitigated to acceptable levels without excessive cost.

The increased capacity of the ventilation system due to the longer drive length is a given condition that has to be addressed in both the design and construction. With regards to this study risks associated with the ventilation requirements raised by the longer tunnel drive length can be defined and mitigated to an acceptable level with well-defined cost.

There is no accepted standard to measure abrasion wear in soil. The abrasion-caused wear rate appears to vary as a function of applied power by the TBM to the soil as well as the soil abrasive properties. Contractors use soil conditioners to reduce the wear but consider this action as proprietary and do not want to publish their approach to mitigation of the wear issue. The approach they use for interventions vary also and often require some form of ground modification to provide a stable and safe environment for the tunnel crew to perform their inspections and maintenance duties on the TBM. The most common ground modification for an intervention is compressed air. Other techniques such as grouting or ground freezing have been successfully used also. As a result we have identified information on interventions on the articles where the information is presented but have not specifically benchmarked this parameter. Consequently, budget and schedule impacts associated with this risk are not well defined. Good evidence is provided by the Brightwater project (see Appendix B). In that project soil abrasion stopped the original slurry TBM, whereas the EPB TBM equipped with hydraulically operated flood doors performed 14 man-entry interventions in very stiff clay at atmospheric pressure to inspect and change cutters for the 3 km of tunnelling to connect with the stuck TBM. Water pressures at these interventions were as high as 5.3bars. The ability to monitor the behaviour of the TBM is a major means of mitigating risks associated with issues that arise with soil abrasion.

The potential cost and schedule impacts of Alternative A are presented in Table ES - 1.

Table ES -1: Summary of Risk Consequences for Alternative A

Alternative	Impact to Budget	Impact to Schedule
A -Elimination of Carnwath Road Riverside Shaft	± 2% Preferred Scheme (preferred scheme overall range £1.4bn - £2.2.5bn)	Over 1 year addition to the critical path (it is noted that significant schedule savings could be made by using a single-pass lining system rather than the proposed two-pass system - (see Section 6.2.1 for further details)).

These impacts to budget and schedule are relative to the average budget range and a calculated schedule based on tunnel and shaft construction rates for the Preferred Scheme as detailed in the Official Journal of the European Union notice dated July2013.

At the start of this study several criteria were raised for assessment against Alternative A and B. These criteria are presented both by CDM Smith and in part based on opinions stated by Thames Water previously to the LBHF suggested Alternative A. With our tunnel design experience we have encountered these same concerns on several projects and have provided our expert opinion based on the limited information we presently have and our understanding of the project. The summary of findings for Alternative A are presented in ES- 2.

Table ES-2: Summary of Findings for Alternative A drive strategies in comparison with the Preferred Scheme

Opinion Stated	Comparative Criteria from Preferred Scheme	Impact of Alternative A
Schedule	Approx. 6 years proposed by Thames Water (scheduled 2016 - 2023)	Over 1 year addition to the critical path (it is noted however that significant schedule savings could be made by using a single-pass lining system rather than the proposed two-pass system (see Section 6.2.1 for further details)).
Budget	1.6bn (Range of costs between £1.4bn - 2.2.5bn proposed by Thames Water)	± 2% Preferred Scheme
Impact on contract size for tender	Three Contract Lots with maximum size of any one Lot estimated at £950M	No significant difference to preferred scheme (however would require a reorganization of contract structure/Lots)
Impact on safety due to drive length	Risks associated with safety are always taken very seriously by the industry and are mitigated to the extent possible.	Additional Health and Safety risks include greater travel times to egress points. It is our opinion that with proper precautions and good tunnelling workmanship increased risks can be mitigated to level of a very slight risk.
Avoidance or impact to existing infrastructure	Issue relates to clearance over the Lee Valley Raw Water Main and under the proposed National Grid Wimbledon to Kensal Grid Cable Tunnel. It is unclear the full extent of tunnel clearance that is intended to be achieved however assume 3m (which is the stated minimum clearance)	Despite increased tunnel diameter in Alternative A, it is our opinion that with proper precautions and good tunnelling workmanship crossing under and over these obstacles can be achieved with little to no impact to the in place structure. Significantly closer clearances have been performed without damage to the existing infrastructure
Risk Contingency applied by contractors as a function of tunnel length	This is a risk that is dependent upon the distribution of risk as stated in the contract documents	Additional risk is very manageable as this tunnel drive length has been achieved several times in the industry
Stakeholders	Stakeholder impact on the preferred scheme which would be impacted by Alternative A relates to Stakeholders at the three main Shafts involved Acton Storm Tanks, Carnwath Road and Kirtling Street.	Less risk at Carnwath Road because of the elimination of the shaft, possible increase in risk at Acton Storm Tanks/Kirtling Street

Table ES-2: Summary of Findings for Alternative A drive strategies in comparison with the Preferred Scheme continued …

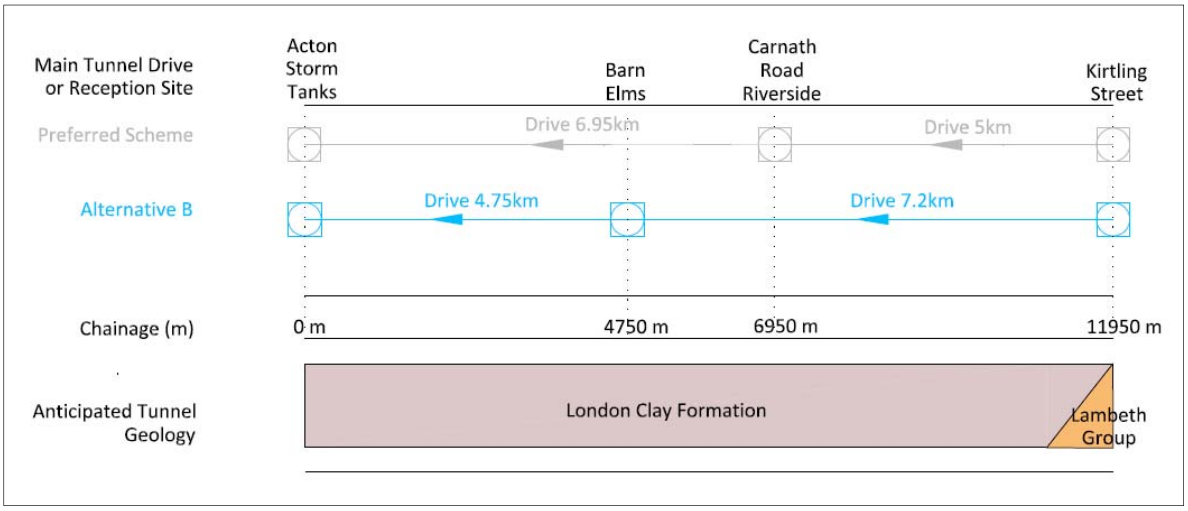
Opinion Stated	Comparative Criteria from Preferred Scheme	Impact of Alternative A
Long term maintenance and worker safety	Criteria related to Alternative A over preferred scheme relates primarily to longer tunnel for egress, and issues related to maintain access.	Minimal increase that can be mitigated
Long term ventilation strategy	For Alternative A this issue relates to the removal of Carnwath Road as the principal active ventilation site for the Thames Tideway Tunnel.	Minimal increase that can be mitigated

ES - 2 Alternative B - Thames Water Phase 1 Drive Strategy including Barn Elms as drive site instead of Carnwath Road

A second alternative drive strategy was also reviewed, Alternative B as follows;

Alternative B: Thames Water Phase 1 Drive Strategy including Barn Elms as drive site instead of Carnwath Road - this alternative reconsiders the Thames Water phase 1 alignment which included Barn Elms as a main drive site rather than Carnwath Road. In this alternative, ventilation facilities proposed for Carnwath Road in the preferred scheme are relocated to Barn Elms. This alternative results in a 4.75km drive from Barn Elms to Acton Storm Tanks and a 7.2km drive from Kirtling Road to Barn Elms using, as in the preferred scheme, an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). At the Barn Elms site the tunnel diameter is reduced from 7,200 mm to 6,500 mm. This change in diameter occurs at the Carnwath Road site in the preferred alignment

Figure ES-2: Alternative Drive Strategy - Alternative B Overview Sketch



Alternative B is not dissimilar to the existing scheme and as a result Alternative B was found to be technically feasible with no major increase in cost or schedule

The potential cost and schedule impacts of Alternative B are presented in Table ES - 3.

Table ES -3: Summary of Risk Consequences for Alternative B

Alternative	Impact to Budget	Impact to Schedule
B - Barn Elms Site used in lieu of Carnwath Road Riverside for shaft	No significant impact*	No significant impact

*Alternative B did not include a range of costs that could not be estimated with the limited data available including the ability to use larger barges at Carnwath Road than Barn Elms, increased site setup/enabling costs and variations between Carnwath Road and Barn Elms of site value/resale value.

Section 1 Introduction

This document summarizes CDM Smith's expert review for the proposed Thames Tideway Tunnel (referred to in this document as the "preferred scheme") and specifically evaluates two alternative drive strategies in response to the request by LBHF. CDM Smith's approach to carrying out our review was to:

- Review available information on the planning, approaches and assumptions that have been taken by Thames Water.
- Conduct a benchmarking study of the issues and or technical parameters considered most important for this project as related to the two alternative drive strategies.
- Identifying the major risk considerations of the issues and parameters under consideration of the two alternative drive strategies in comparison to the preferred scheme.
- Perform a risk evaluation for the items identified above specifically for two alternatives to the current planning of shaft location and spacing with regards to tunnel drive length for the proposed Thames Tidewater Tunnel project.
- Prepare this report and provide expert consulting before and possibly during the scheduled public meetings.

A draft of this report was submitted to LBHF on 25 October, 2013. CDM Smith participating in a conference call review of the draft report on 29 October, 2013. This final report incorporates revisions and additions to the draft report based on comments received from the client team as a result their review of the draft report and review conference call.

The TTT, as proposed by Thames Water Utilities Ltd. (Thames Water), is a proposed wastewater storage and transfer scheme that would capture combined sewer overflows prior to their overspill of untreated wastewater and rainwater runoff into the Thames estuary. The project is currently in the conceptual design phase and was submitted to the Planning Inspectorate on February 28 2013 for Development Consent. The examination of the submission will include hearings in November 2013. In July 2013 a formal call for competition was made in the Official Journal of the European Union (OJEU) for tenderers for the TTT divided into three Contract Lots as shown in Table 1 - the tenders were due to be returned by 13 September 2013. Thames Water announced the shortlisting of the tunnelling contractor teams on October 29 2013 for the three proposed contracts (Thamestidewaytunnel.co.uk, 2013). The preferred bidder is expected to be announced in early 2015 with construction (total expected duration of six years) anticipated to commence in 2016.

Table 1: Thames Tideway Tunnel Contract Lots as issued to Tender in July 2013

Lot	Contract Name	Estimated Range (£M)
Lot 1	C405 Thames Tideway Tunnel - Main Works - West	300 - 500
Lot 2	C410 Thames Tideway Tunnel - Main Works - Central	600 - 950
Lot 3	C415 Thames Tideway Tunnel - Main Works - East	500 - 800

1.1 Brief History of Thames Tideway Tunnel Project

London's sewer system was designed in the 1880's to handle wastewater and surface drainage runoff through a combined system (CSO). The Environment Agency assessed the CSO discharges in the Beckton and Crossness catchments. This assessment showed that 36 CSO's were identified as "unsatisfactory" and

required attention. Of this total 34 CSO's discharge into the tidal Thames and two into the River Lee (Thames Water (Doc Ref 7.18), 2013).

When completed the Thames Tidewater Tunnel project will connect to the Lee Tunnel and comprise a full-length tunnel to store and transfer discharges from west to east London to Beckton Sewerage Treatment Works (STW). The primary objective is to control discharges to meet the requirements of the European Union Urban Waste Water Treatment Directive (91/271/EEC) (UWWTD) and the related United Kingdom (UK) Urban Waste Water Treatment Regulations.

The tunnel alignment follows the Thames River. In general the subsurface conditions expected to be encountered consist of recent alluvium deposits consisting of soft clay and medium to dense sand and gravel that could extend to a depth of 5 to 15 m. Underlying this is the London Clay, a very stiff fissured clay. The tunnel heading from the Acton Storm Tanks for about 9km will be in this clay. Underlying the London Clay is the Lambeth Group of which the upper 10 to 20 m consists of stiff clay. The lower 5 to7 m of the Lambeth Group is gravel with sand, silt and clay. The tunnel heading will be in the Lambeth Group for about 8.7 km. The underlying stratum is the Thanet Sand formation, very dense silty sand. This stratum is only 10 to 15m thick and the tunnel will be in it for about 0.5km. Underlying this sand is the Chalk in which the tunnel heading will stay for about 7.2 km to the eastern terminus of the Project at Abbey Mills.

Of the 34 CSO discharge location on the Thames Tidewater Tunnel 18 will have flow control by diverting flow into the main tunnel.

The CSO's that will be controlled by diverting flows into the main tunnel and therefore require a worksite are:

- Acton Storm Relief (Proposed Site: Acton Storm Tanks)
- Hammersmith Pumping Station (Proposed Site: Hammersmith Pumping Station)
- West Putney Storm Relief (Proposed Site: Barn Elms)
- Putney Bridge (Proposed Site: Putney Embankment Foreshore)
- Frogmore Storm Relief Proposed Sites: Dormay Street and King George's Park)
- Falconbrook Pumping Station (Proposed Site: Falconbridge Pumping Station)
- Lots Road Pumping Stations (Proposed Site: Cremorne Wharf Depot)
- Heathwall Pumping Station (Proposed Site: Heathwall Pumping Station)
- South West Storm Relief (Proposed Site: Heathwall Pumping Station)
- Clapham Storm Relief (Proposed Site: Albert Embankment Foreshore)
- Brixton Storm Relief (Proposed Site: Albert Embankment Foreshore)
- North East Storm Relief (Proposed Site: King Edward Memorial Park Foreshore)
- Earl Pumping Station (Proposed Site: Earl Pumping Station)
- Deptform Storm Relief (Proposed Site: Deptford Church Street)
- Greenwich Pumping Station (Proposed Site: Greenwich Pumping Station)

Three other CSO's would also be controlled by diverting their flows into the Main tunnel adjacent to a local connection to the existing northern Low Level Sewer No. 1.

- Ranelagh (Proposed Site: Chelsea Embankment Foreshore)
- Regent Street (Proposed Site: Victoria Embankment Foreshore)
- Fleet Main (Proposed Site: Blackfriars Bridge Foreshore)

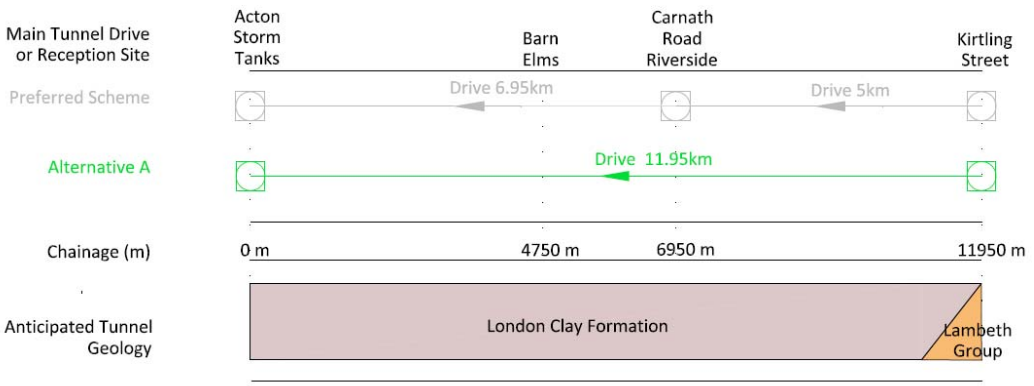
1.2 Alternative Drive Strategies

CDM Smith's evaluation and review included consideration of the engineering and technical issues of the preferred alignment and consideration of the two alternative alignments proposed by LBHF;

The two alternative drive strategies are;

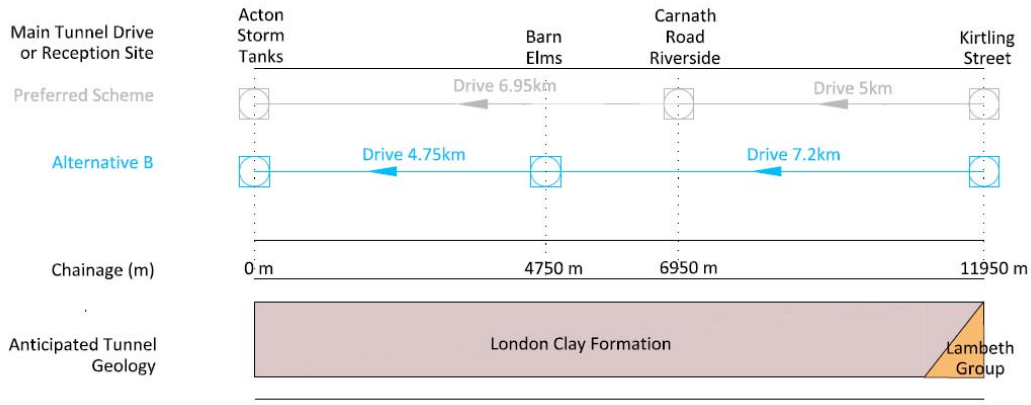
1. **Alternative A: Alternative Drive Strategy excluding Carnwath Road drive site** - this alternative follows the current Thames Tideway Tunnel alignment but excludes the drive shaft and long term ventilation facility at Carnwath Road. In this alternative, active ventilation facilities are proposed at either end of the Thames Tideway Tunnel - at Acton Storm Tanks, and at Abbey Mills Pumping Station (with the remainder of the existing TTT Air Management Plan (Thames Water, 2013) unaffected). This alternative results in a single 12km drive from between Acton Storm Tanks and Kirtling Street at 7200mID using, as in the preferred scheme, an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM).

   Figure 1: Alternative Drive Strategy - Alternative A - Overview Sketch



2. **Alternative B: Thames Water Phase 1 Drive Strategy including Barn Elms as drive site instead of Carnwath Road -** this alternative reconsiders the Thames Water phase 1 alignment which included Barn Elms as a main drive site rather than Carnwath Road. In this alternative ventilation facilities proposed for Carnwath Road in the preferred scheme are relocated to Barn Elms. This alternative results in a 4.75km drive from Barn Elms to Acton Storm Tanks and a 7.2km drive from Kirtling Road to Barn Elms using, as in the preferred scheme, an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). At the Barn Elms site the tunnel diameter is reduced from 7,200 mm to 6,500 mm. This change in diameter occurs at the Carnwath Road site in the preferred alignment

Figure 2: Alternative Drive Strategy - Alternative B Overview Sketch



These alternatives are evaluated in terms of risk in comparison to the documents and drawings prepared as part of the Thames Water Utilities Ltd. (Thames Water) Application for Development Consent to the Planning Inspectorate dated, January 2013 as found on the National Infrastructure Planning portal (http://infrastructure.planningportal.gov.uk/projects/london/thames-tideway-tunnel/). In addition the TTT website (www.thamestidewaytunnel.co.uk) was heavily referenced as the site that contains a full progression of the preliminary design process. A full list of references is included in Section 7.

It should be noted that the current Thames Tideway Tunnel as submitted for application for Development Consent will be referred to as 'preferred scheme' in this report.

1.3 Methodology

All tunnelling projects involve several different areas of risk, with their own probabilities of occurrence, impact to budget and impact to schedule. The combinations of risks, their probability of occurrence and consequence of occurrence to a project will be different for each project. When the value of any one parameter that is component of a risk is changed, the project impact in terms of both budget and schedule will also change. The level of change to budget and schedule can be evaluated based on assumed conditions, the changes to certain parameters and experienced engineering judgment in terms of quantifying the risk. To accomplish the evaluation of risks for the proposed alternatives schemes we began by understanding the Thames Water preferred scheme.

To understand the project we first reviewed the available documents and relied heavily upon the information presented in the submitted Engineering Design Statement (Doc Ref: 7.18) (Thames Water, 2013) as the basis to evaluate changes to the program due to considered alternatives. Based on this data review we formulated an understanding of the overall subsurface conditions for the preferred tunneling scheme [Section 2].

To accomplish this evaluation we followed the four-step sequence described below:

Firstly we identified risks associated with each proposed alternative drive strategy as compared with the preferred scheme [Section 3]. Risks identified are major risks associated with this early stage in the project development most likely to differ from the preferred alignment in terms of probability of occurrence and consequence of occurrence.

Secondly we completed a benchmarking study (see Section 4) to understand the issues associated with tunnel drive length in terms of what has been done in prior tunnelling projects of similar size and conditions and some of the lessons learned from those projects. Lessons learned from prior projects are an excellent means of identifying and mitigating future risks. As part of this benchmarking review of published literature

of tunnel projects with similar features, we also performed a review of our own in-house projects that involved similar risks where we could identify lessons learned that may be of use to mitigate similar risks on this project, and finally reviewed advances in TBM machine technology.

Thirdly, in Section 5, an @Risk Model is developed to attempt to assess the impact on cost and schedule of the two alternatives in comparison to the preferred scheme. @Risk is risk and decision analysis software that allows the many possible outcomes of a scenario to be simulated, and the likelihood of occurrence determined. We use @Risk to enable a broad understanding of the two alternatives to be assessed from a cost and schedule perspective.

Finally the risk evaluation of both suggested alternatives relative to the preferred scheme was then completed relying both on the results of the benchmarking exercise, @Risk model results and also on assumed parameters based on available information or professional judgment. Section 6 of the report is our summary of our findings and conclusions.

LBHF has previously approached Thames Water in relation to the first proposed alternative, Alternative A (alternative drive strategy excluding Carnwath Road as a main tunnel drive site). Thames Water has returned a series of eight obstacles to the proposed Alternative A. All eight obstacles to the proposed alternative drive strategy (Alternative A) are valid issues and we have provided a professional opinion on each should they be encountered. Some of these obstacles are also pertinent to the second alternative (Alternative B) which would use Barn Elms as the main tunnel drive site instead of Carnwath Road Riverside. The response to the obstacles, which are included in the below criteria for assessment, are provided in the body of this report.

1.4 Criteria for Assessment of Alternative A and B

The two alternatives have been evaluated based on safety, cost, and schedule. There are many issues that affect those parameters. The goal of this study was to evaluate how those parameter values can change due to adoption of either of Alternative A or B. The below nine criteria for assessment include the eight obstacles presented by Thames Water to Alternative A.

Criteria for Assessment are as follows:

- *Schedule* – Based on the benchmarking of projects of similar tunnel size and length and using our experience we applied a probability distribution to the given advancement rate parameter for shaft and tunnel construction. We used the @RISK software to help develop a probable range in effect to the schedule for the alternatives. The results of this analysis are then compared to the schedule presented in the proposed TTT Application for Development Consent documents.

- *Budget* – The risk of a deviation to the budget was evaluated in a similar manner to that used for the Schedule. The approach used to assign a cost to the variance was based on the general cost budgeted for the shaft and tunnel construction cost applied as a unit hourly. The resulting risk to the budget was then determined as the product of unit hourly cost rate multiplied by the change to the schedule. The same model is used to evaluate probable range in budget as a result of these alternatives. The results of this analysis are then compared to the schedule presented in the proposed TTT Application for Development Consent documents. Assessment of impact to Budget includes requirement for additional interventions to inspect and maintain the TBM, increased risk of TBM failure over a longer tunnel drive and positive budgetary impacts such as removal of Carnwath Road shaft construction costs.

- *Impact on Contract Size for Tender* – The larger the contract size the fewer single entities will be able to bid the project. However, joint ventures for tunnel work are common today. The criterion this parameter is measured against is the current size of major tunnel projects. This parameter is

not directly used in the @RISK model. We have provided a professional opinion on the issue of the impact on tender of a contract size. It is noted that Thames Water recently announced the shortlisting of eight tunnelling contractor teams for the three proposed Contracts Lots (Thamestidewaytunnel.co.uk, 2013) seven of which are joint venture teams, with one contractor Bouygues Travaux Publics acting as a single applicant (see Table 2.)

Table 2: Contractor Teams shortlisted for Preferred Scheme on October 29 2013 (Thamestidewaytunnel.co.uk, 2013)

Lot 1 - West	Lot 2 - Central	Lot 3 - East
Bam Nuttall/Balfour Beatty/Morgan Sindall JV	Bam Nuttall/Balfour Beatty/Morgan Sindall JV	Bam Nuttall/Balfour Beatty /Morgan Sindal JV
Costain/Vinci/Bachy JV	Costain/Vinci/Bachy JV	Bechtel/Strabag JV
Dragados/Samsung JV	Ferrovial Agroman/Laing O'Rourke JV	Bouygues Travaux Publics
Ferrovial Agroman/Laing O'Rourke JV	Skanska/Bilfinger/Razel Bec JV	Costain/Vinci/Bachy JV
		Hochtief/Murphy JV

- *Impact on Safety due to drive length* – There are two significant impacts that a very long tunnel drive will have regarding risk to safety. One is the ability to properly and continuously ventilate the tunnel. The second risk involves the time lag in providing medical attention should an incident arise.. This parameter is not directly used in the @RISK model. We have provided a professional opinion on the issue.

- *Avoidance or impact to existing infrastructure* –We have rendered an opinion regarding risk exposure of this parameter as it relates to a step change proposed in the preferred scheme between TTT crossings of the Lee Valley Raw Water Main Tunnel and the Proposed National Grid Cable Tunnel.

- *Risk contingency applied by contractors as function of tunnel length* – There is a risk associated with the tunnel length that each bidder will apply to their proposal. The magnitude of the risk will be judged by each bidder based on how the owner delegates the ownership of the risk, how it is paid for in the contract documents and the detail and quality of the pertinent data that is required to make an informed decision on the risk item. We have provided a professional opinion on the issue of the impact on tunnel drive length.

- *Stakeholders* – There is an impact to stakeholders with regards to the construction duration due to the alternatives. Much of this impact is subjective in nature. Objective comparisons can only be made of parameters such as change of construction duration of work at a shaft site and changes in spoil hauling as a change in number of trucks/barges used on a daily basis and impact to the local traffic.

- *Long Term Maintenance and worker safety* – The tunnel length will be a long term risk regarding worker safety. Specific major risk items are working in a confined space and distance between tunnel egresses locations. We have identified what are preliminary but realistic travel times to get to egress points in the tunnel and have detailed risks and mitigation measures available in this regard. In particular LBHF have also proposed the use of CSO shafts as access/egress locations. We have provided a professional opinion on this issue.

- *Long Term Ventilation Strategy* - Thames Water have created an Air Management plan for the long term ventilation of the TTT. A Thames Water identified obstacle to Alternative A is that the ventilation strategy would need to be reconsidered. In addition LBFH have proposed the use of CSO shafts as active ventilation sites. We have provided a professional opinion on this issue.

Section 2 Geologic Conditions and Alignment

2.1 Geologic Conditions

The geology of the London Basin that the TTT will be encountering consists of three eras of deposition; recent, tertiary and cretaceous. A general description of the geologic conditions subsurface profile is presented inTable 3.

The geology description summary is from the Engineering Design Statement report. The descriptions of the tunnelling ground conditions presented in the following subsections are based on the assumption that each of the formations listed in this subsurface profile table is present in the profile and to the approximate thicknesses listed in the table. Groundwater is assumed to have a hydraulic connection with the Thames Estuary with the probable exception of tunnel segments tunnelling below the London Clay where excess hydrostatic heads are to be anticipated.

Table 3: Geologic Conditions

Era	Group	Formation	Description	Thickness Range, m
Recent		Alluvium	Soft clays, silts, sands and gravels – may contain peat	0 to 5
		Floodplain Terrace	Medium to dense sand, flint, chert gravel, occasional cobbles and boulders	0 to 10
		Kempton park Terrace		
Tertiary	Thames	London Clay	Very stiff fissured silty, occasionally slightly sandy clay	>100
		Harwich	Swanscombe Member: Sandy clay to clayey sand some rounded gravel (< 2m)	0 to 10
			Blackheath Member: Dense to very dense flint gravel, occasional cobble in silty to clayey fine to medium sand matrix	
			Oldhaven Member: Very dense clayey sand with gravel and shells – often cemented as limestone	
	Lambeth Group	Woolwich	Stiff, clay with locally abundant shell debris and strong limestone beds (100 to 200mm thick)	10 to 20
		Reading	Very stiff to hard sandy clay	
		Upnor	Gravel, organic sand silt and clay	5 to 7
	Thanet Sand Formation (including Bullhead Bed at base, < ~0.5m)		Very dense silty to very silty sand Lowest ~0.5m sometimes consists of fine medium coarse angular flint gravel	10 to 15
Cretaceous	Chalk	Seaford	Homogeneous chalk with nodular flint horizons (>100mm thick)	Circa 40
		Lewes	Heterogeneous nodular chalk with nodular flint horizons and marl seams	Circa 50

2.2 Tunnel Alignment by Contract

The Combined Sewer Overflow (CSO) program as presently proposed in the Engineering Design Statement report will consist of an overall length of the main tunnel of 25.2km from Acton Storm Tanks to Abbey Mills Pumping Station. From Abbey Mills to the Hammersmith Pumping Station tunnelling will be performed largely beneath open water following the meandering path of the Thames Estuary. The total alignment contains 42 curved sections of tunnel footage which represent approximately 40% of the total length(see Appendix C for alignment calculations). At the Hammersmith Pumping Station the alignment crosses under the Thames twice as the river twists to the south and the tunnel alignment advances Storm Tanks as an under land (as opposed to under open water) tunnel in a north-westerly direction toward Acton.

Our understanding of alignments and expected general conditions are as described below. These descriptions are organized based on the three contract lots as issued in the Thames Water Tender Notice (OJEU, July 2013).

2.2.1 Lot 3 - Main Works - East: Chambers Wharf to Abbey Mills Pumping Station

The work in this section will be in one contract. This tunnel in this Lot is 5.53km in length and will have a 7,200mm inside diameter. The tunnel drive will be up gradient. The first half predominantly is under the Limehouse Cut canal and the remainder is under the Thames Estuary. The tunnel alignment has a total of six curved sections all with a radius of 600m. The lengths of the curves range from 107m to 435m. Approximately 25% of the alignment is on curved sections.

This entire length of tunnel will be in the upper portion of the Seaford Formation of the Chalk Group. The Engineering Design Statement report (Thames Water (Doc Ref: 7.18), 2013) indicates that this tunnel will be excavated using a slurry TBM.

2.2.2 Lot 2 - Main Works - Central: Kirtling Street to Chambers Wharf and Kirtling Street to Carnwath Road Riverside

This work will be in one contract and consist of two tunnel drives both starting at the Kirtling Street site. The first tunnel from Kirtling Street to Chambers Wharf segment will consist of 7.67km of 7,200mm Internal Diameter (ID) tunnel. This tunnel will be driven down gradient. The entire length of the tunnel will be under open water following the meandering path of the Thames Estuary. This tunnel segment has 10 curved sections all with a radius of 600m. The lengths of the curves range from 55m to 325m. Approximately 20% of the alignment is on curved sections.

Starting at the Kirtling Shaft, the tunnel will be driven in a mixed face condition. Most of the tunnel face will be in the Lambeth Group consisting of the stiff clay of the Woolwich Formation. The upper portion of the tunnel face is expected to be in the lower portion of the very stiff fissured London Clay formation. The Lambeth group contains more sand than the London Clay and could be expected to be more abrasive than the clay. As the TBM advances the heading will vary from full face of the Lambeth Group to mixed face with the London Clay for about 4 km. Along this segment the Lambeth Group will transition with depth from stiff clay to hard sandy clay (Reading Formation) to gravel with sand, silt, and clay (Upnor Formation). At about 4 km the tunnel heading will start to encounter another mixed face consisting of the Upnor Formation overlying the Thanet Sand formation and in some reaches the heading will be full face of the Upnor Formation. About 1km from the Chambers Wharf shaft the heading will start to transition to a full face of the Seaford Chalk and remain in that material to the Chambers Wharf shaft site. The Engineering Design Statement report (Thames Water (Doc Ref: 7.18), 2013) indicates that this tunnel will be excavated using an EPB TBM.

The second tunnel drive on this contract will also start from the Kirtling Street Shaft and will extend to Carnwath Road Riverside a distance of 5km and will have a 7,200 mm ID. This tunnel will be driven up gradient. The entire length of the tunnel will beneath open water still following the winding path of the Thames Estuary. This tunnel segment has 11 curved sections all with a radius of 600m. The lengths of the curves range from 180m to 775m. Approximately 70% of the 5km alignment is on curved sections.

At the Kirtling Shaft the tunnel will be in the same mixed face condition as the Kirtling Street to Chambers Wharf segment. However the geological profile (Thames Water (Doc Ref: 9.18), 2013) indicates that at distance of only about 100m from the shaft the underlying Woolwich Formation drops to below the tunnel invert and the tunnel heading will be in a full face of the lower portion of the London Clay. The profile is not clear with regards to the presence of the Harwich Formation that is between the overlying London Clay and the underlying Woolwich Formation of the Lambeth Group. This Harwich formation is listed as 0 to 10 m thick. For the first 3km of this drive the alignment is predominately in the London Clay. The tunnel invert will be near the interface of the underlying Woolwich Formation. At this point the tunnel interface rises above the interface of these two formations and the tunnel heading is all in the London Clay. The Engineering Design Statement report (Thames Water (Doc Ref: 7.18), 2013) indicates that this tunnel will be excavated using an EPB TBM.

2.2.3 Lot 1 - Main Works - West: Carnwath Road Riverside site to Acton Storm Tanks

From Carnwath Road Riverside to Acton Storm Tanks the tunnel diameter is reduced to 6,500mm ID. This tunnel is over a distance of 6.95km. The first part of this alignment from Carnwath Road Riverside (approx. chainage 6900) to the connection tunnel (approx. chainage 3050) from the Hammersmith Pumping Station continues to follow directly below the Thames Estuary and contains six curved tunnel sections representing about 35% of the alignment.

This entire tunnel alignment in this section will be tunnelled in the London Clay. The Engineering Design Statement report (Thames Water (Doc Ref: 7.18), 2013) indicates that this tunnel will be excavated using an EPB TBM.

From the Hammersmith Pumping Station connection tunnel the alignment diverges from the Thames Estuary. The upstream continuation of the river is to the south whereas the tunnel heads in a westerly direction toward the Acton Storm Tanks. This portion of the alignment has eight curved sections. Because of the reduced tunnel diameter the curve radii have been reduced to 500m for one curve and the remaining seven curves have 400m radii. The curved portions of the tunnel from the Hammersmith connection tunnel to Acton Storm Tanks represent 60% of the tunnel length.

From the Acton Storm Tanks to the Hammersmith Pumping Station connection tunnel, a distance of 3,050 m, the tunnel alignment is under land with the exception of crossing under the Thames Estuary twice. A total of about 2,600 m of the tunnel is under land. However, approximately 1 km of this same segment of tunnel is under existing structures.

Section 3 Alternative Drive Strategies

Two alternative drive strategies are assessed in this report. A description of the two alternatives is provided below. This is followed with a list of risks identified for each of the alternatives.

3.1 Alternative A: Alternative Drive Strategy excluding Carnwath Road Riverside Drive Site

The Carnwath Road Riverside shaft is at chainage 6950. In the preferred scheme the drive length from Kirtling Street to Carnwath Road Riverside is 5.0km and is proposed to be driven using an EPB machine with a finished diameter of 7,200mm.

Alternative A proposes to eliminate the Carnwath Road Riverside main tunnel drive site. This will require that the tunnel be driven from Kirtling Street to the Acton Storm Tanks which adds the 5.0km of tunnel drive length to the 6.95km distance from Acton Storm Tanks to Carnwath Road. The resulting drive length from Kirtling Street to the Acton Storm Tanks would be approximately 11.95km. The 6.95km drive from Acton Storm Tanks to Carnwath Road Riverside had been intended to be 6.5m ID. In this alternative the entire tunnel would be 7.2m ID.

It should be noted that if the internal diameter were reduced to 6.8m ID along the 11.95km drive, that the same storage capacity could be retained along the length of the tunnel. This would result in cost savings on this Alternative. Any reduction in diameter would require a reconsideration of the hydraulics assessment. A reconsideration of the hydraulics assessment is beyond the scope of this report.

3.2 Alternative B: Thames Water Phase 1 Drive Strategy including Barn Elms as drive site instead of Carnwath Road

This alternative would replace the main tunnel drive site at the Carnwath Road Riverside site with a main tunnel drive site at the Barn Elms site. This alternative was the Thames Water preferred option for the Phase 1 public consultation round, however was replaced in Phase 2 by the Carnwath Road Riverside location after a technical review of acceptable shaft sites. It should be noted that both Barn Elms and Carnwath Road Riverside are considered 'suitable' drive sites by Thames Water however Carnwath Road Riverside was ultimately selected.

We assume that the ventilation system to be part of the facilities at Carnwath Road Riverside site would be part of Barn Elms infrastructure

The Barn Elms site is approximately 15 hectares of which a portion would be used for construction. The site is a less urbanized area than the Carnwath Road Riverside site. By using this site as an exit shaft of the tunnel and future ventilation structure for the completed tunnel, the drive length from Kirtling Street to Barn Elm is 7.2km rather than the 5.0km to Carnwath Road Riverside in the preferred scheme.

Under this alternative the tunnel diameter will remain at 7200mID until the Barn Elms shaft site whereupon it will be reduced via the Barn Elms to Acton Storm Tanks drive (4.75km, 6500mm ID). The effect on the project of changing tunnel size at Barn Elms means an additional 2 km of tunnelling with a larger diameter tunnel than is required in the preferred scheme. The advantage of the 2km of larger diameter shaft means an increase in tunnel storage of 18,300m^3 whilst the disadvantage is the cost associated with this larger diameter over that distance.

It should be noted that the if the internal diameter were reduced to 6.1m ID along the 4.75km drive between Barn Elms and Acton Storm Tanks, that the same storage capacity could be retained along the length of the tunnel. This would result in cost savings on this alternative. Any reduction in diameter would require a reconsideration of the hydraulics assessment. A reconsideration of the hydraulics assessment is beyond the scope of this report.

3.3 Identified Risks of Alternative A and B

The two alternatives raise several design and construction issues that have been evaluated with respect to the benefit in comparison to potential impacts to both project schedule and project cost. The issues evaluated and why we consider them to be risks are described in the following text. It is very important to note that these risks already exist to some degree with the preferred scheme. This report evaluates the changes in the probability of a risk occurring due to the alternative drive strategies proposed and the consequences of such an occurrence. The same risk issues are present for both alternatives. The difference is primarily a function of tunnel drive length.

3.3.1 Risks due to Increased Tunnelling Length

Tunnelling under open water presents a risk with expensive consequences if the TBM should become stuck. The reason for a machine getting stuck is that it gets worn down to the point that it cannot advance without major repairs. The reason for the high costs is limited means of accessing the machine, specifically the face of the machine that is in contact with the soil. The longer a tunnel drive the more wear that will occur to the TBM, specifically the cutters, exposed wearing surfaces and main bearings. The rate of wear on the exposed equipment is a function of the ground abrasiveness, and the workmanship of the TBM operator. The means of mitigating this wear consists of: making the machine sufficiently rugged to withstand the tunnelling conditions, inspecting the cutters on a more frequent basis, followed by changing cutters on a more frequent basis to protect the other parts of the machine from wear and to treat the soil to reduce its abrasiveness.

The wear rate on a soft ground tunnel machine is not as well documented as it is for a rock tunnel, nor is the ability of the design engineer to objectively quantify the abrasiveness of the soil as it is in for rock tunnels. As the tunnel length increases the risk of a TBM wearing to the point that it cannot advance also increases. There are precautions that can be taken both in design and during construction to help mitigate this failure of a TBM but they are still risks of TBM failure that need to be considered.

3.3.2 Risk of Insufficient Clearance to Infrastructure Adjacent to Tunnel Heading

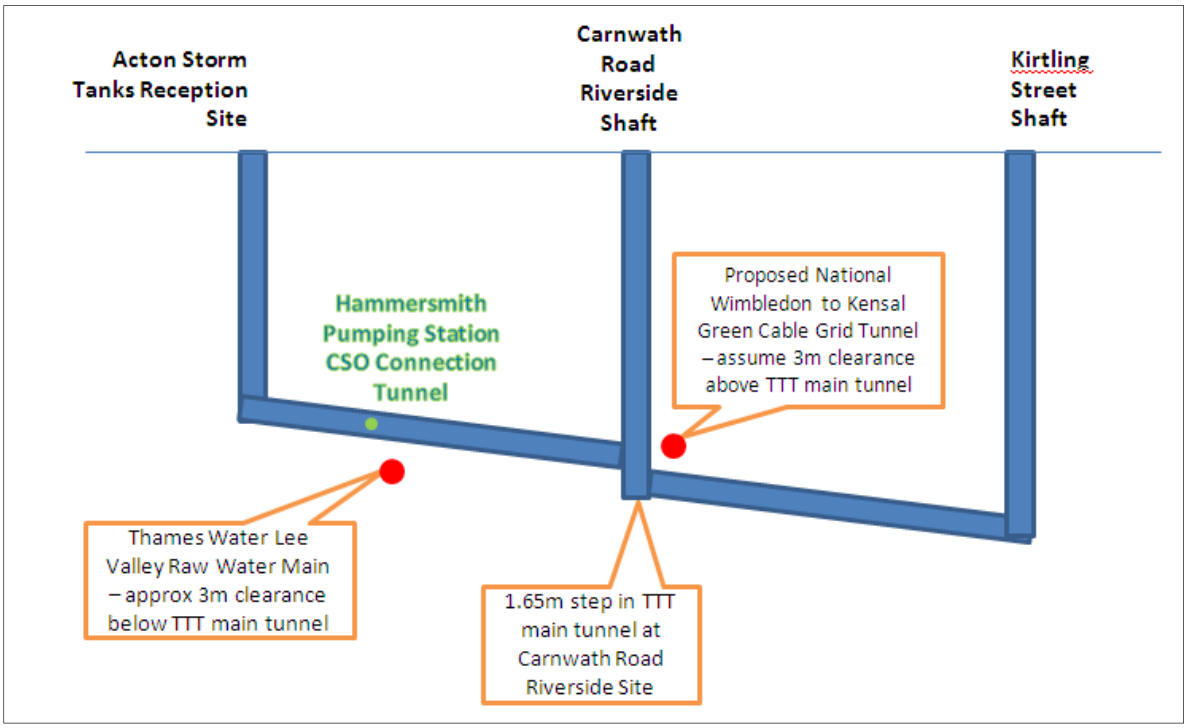
As identified by Thames Water in a letter to LBHF in December 2011, a potential obstacle of Alternative A is the requirement to meet strict vertical clearances between two pieces of infrastructure that cross above and below the preferred scheme tunnel drive. The Engineering Design Statement report (Thames Water (Doc Ref: 7.18), 2013) notes that the minimum clearance of the main tunnel in the preferred scheme to infrastructure is 3m.

The first piece of infrastructure in question is the existing Thames Water Lee Valley Raw Water Main just east of Hammersmith Pumping Station. The preferred scheme has a design tunnel clearance of 3.4m above the Lee Valley Tunnel according to the Tunnel And Bridge Assessment (Thames Water (Doc Ref: 9.15.07), 2013) which is located just east of Hammersmith Pumping Station (see Figure 3). The second piece of infrastructure is the proposed National Grid (NG) Wimbledon to Kensal Green Cable Tunnel. The clearance below the NG cable tunnel to the preferred scheme is unclear from available documents noted as 6m according to the Tunnel And Bridge Assessment (Thames Water (Doc Ref: 9.15.36), 2013) or approximately 4m if measured from the Book of Plans (Thames Water (Doc Ref: 2.01), 2013). In other words, the vertical

alignment of the preferred tunnel scheme is restricted between these two existing utility tunnels. The report will assume that the clearance between the preferred scheme and both the Lee Valley Raw Water Main tunnel and the NG Cable Tunnel are 3m due to lack of clarity in available source documents.

The preferred scheme uses the Carnwath Road Riverside shaft to create a 1.65m step in the alignment to provide aid vertical clearance above the Lee Valley Water Tunnel (to the west) and below the proposed National Grid Cable Tunnel (to the East) (see Figure 3).

Figure 3: Sketch of Adjacent Infrastructure Clearances required for Preferred Scheme



Alternative A includes a 12km tunnel between Kirtling Street and Acton Storm Tanks of 7200mm ID. Alternative A therefore has to tackle two increased risks to vertical alignment:

1) The tunnel diameter increases between Carnwath Road Riverside and Acton Storm Tanks from the preferred scheme design diameter of 6.5mID to 7.2mID due to the use of a single drive - this is theoretically a 0.35m reduction on clearance to the Thames Water Lee Valley Tunnel.

2) Removing Carnwath Road Riverside removes the ability to insert a step change in vertical tunnel alignment.

The clearance between a source of ground loss such as a tunnel excavation and an existing structure is determined by the ability of a structure to withstand ground deformation, and the magnitude of the ground loss than can be anticipated. The ground loss occurs because the tunnel excavates more ground per meter than is replaced by the finished tunnel in place. For any one incident the movement of ground is smaller the further away from the source of ground loss. The reverse is also true, the closer the spacing between the infrastructure and the tunnel (representing the source of lost ground and subsequent ground and structure movement) the more movement can be expected and the higher the risk of a problem.

Clearance issues are common in tunnelling and can be mitigated by ground modification if deemed necessary during design and construction. Survey control and real time monitoring of TBM alignment have made major advancements in tunnelling technology today and thus can significantly mitigate issues with line and grade of the tunnel during construction.

3.3.3 Risk of Longer Contract Duration

The three most obvious risks to contract duration are both related to the increased tunnel length. Firstly, as the tunnel drive increases, there is an increase in risk to the schedule because of wear to the TBM. As a result of this risk, mitigation approaches generally recommended include the increase in interventions to both inspect and maintain the cutters on the face of the TBM. These actions require TBM downtime and as a result increase schedule and also add expense.

Secondly, a longer drive length adds travel time from shaft to tunnel heading - longer travel time for workers, materials to the heading, and spoil from the heading. This risk can be mitigated through scheduling and use of track switches. A tunnel of 7.2mID would be expected to have a single-line rail track carrying workers and materials to the heading. Switches can be installed to allow 'trains' travelling in opposite directions to pass each other out, reducing or eliminating down time due to delays in getting equipment and materials to the heading. This risk to schedule is therefore not considered significant.

Finally in Alternative A the ability to drive two tunnels concurrently is removed when a single 11.95km tunnel replaces two smaller length tunnels. This extends the contract duration.

3.3.4 Risk of Ventilation Issues

Ventilation becomes a more significant issue with the longer tunnel drive both during construction regarding worker safety and long term maintenance. The long term issues are both worker safety in the tunnel during inspection and maintenance and hydrogen sulphide concentrations that will adversely affect the exposed concrete and 120-year design life of the tunnel.

Ventilation during Construction

Tunnelling work spaces are considered as confined working spaces and safety regulations require specified amounts of air based on crew size and machinery working in the tunnel. This is not perceived to be a risk in a 11.95km tunnel as additional booster fans can be added to ensure legislative requirements are met for the additional length.

Ventilation for Long Term Operation and Maintenance

Requirements for air circulation in the tunnel post construction are also required. The TTT Air Management Plan (Thames Water (Doc Ref: 7.14), 2013) preferred scheme design requires one air exchange per day under the low air flow rate scheme. Air flow and pressure estimates are absent. The design criteria would have to be maintained for the longer length tunnel. This is not perceived to be a major risk but would require the redesign of the current Thames Water proposed Air Management Plan (see Section 6.2.9). It should be noted that operation and maintenance regulations regarding entry into a sewer always require man-entry with personal protective equipment for Confined Space Entry, regardless of the rate of ventilation to the sewer. During man-entry operations the personnel are equipped with personal air supplies and air monitoring equipment, in addition to being tethered to a manned rescue tripod at the surface.

3.3.5 Risk to Safe Egress -

Both during construction and any maintenance work in the tunnel the means of getting personnel out of the tunnel quickly is a function of the distance to the exit shaft. During construction travel time in the spoil carts is usually at a rate of 5 to 15 km/hr depending on load, engine power, grade and curves in the alignment. With use of land based small diameter shafts egress distances can be reduced. Increasing tunnel length can increase risk of safe egress if no additional egress options are planned however mitigation measures are possible. Along the Acton Storm Tanks to Kirtling Street tunnel segment, there are 7 CSO connection points.

CSO shafts and connection tunnels can be designed for access and egress if required. This may require special design consideration of operation and maintenance requirements.

In addition it should be noted that construction is supported by other mitigation measures such as carrying extra air supplies, access to medical equipment and the creation of safe haven locations as part of the construction plan.

Post construction any man-entry to the sewer would have to follow strict Confined Space entry procedures including personnel having appropriate training, the completion of risk assessments prior to access and all personnel being equipped with personal air supplies and air monitoring equipment, in addition to being tethered to a manned rescue tripod at the surface.

3.4 Risk Summary

The same risk issues exist for both alternatives (excepting Section 3.3.2 which only applies to Alternative A). The probability of occurrence of impact to budget and schedule are expected to be greater in the tunnel drive alternative strategies that have greater length that the preferred scheme.

Tunnel drive length is the common factor in most identified risks of proposed Alternative A and B. In Section 4 the length of the Alternative A 12km single-drive tunnel is compared to a database of benchmarked projects.

Alternative A increases drive length which is accompanied with an increase in risk occurrence. However, this alternative eliminates a shaft and its associated cost. This saving also has to be factored into the total evaluation.

In consideration of Alternative B, most of the additional risks to construction considered are related to tunnel drive length. In Alternative B the maximum tunnel drive length is 7.2km between Kirtling Street and Barn Elms, which is shorter than the currently planned longest drive under the contract between Kirtling Street to Chambers Wharf (7.67km). The Barn Elms to Kirtling Street 7.2km drive is expected to be in more consistent tunnelling medium than the 7.67km Kirtling Street to Chambers Wharf segment. As such the risks to schedule and budget for Alternative B are equal or less than that of the Kirtling Street to Chambers Wharf tunnel drive. Alternative B eliminates the requirement for the Barn Elms CSO Connection Shaft and connection tunnel and its associated cost. This saving also has to be factored into the total evaluation.

Section 4 Benchmarking

The aim of this section is to benchmark the risk items identified in Section 3 against best practice to firstly assess if the two Alternatives are technically possible and reasonable given current technologies and standards of practice, and secondly to determine parameters for use in the @Risk Model for cost and schedule determination of the Alternatives (Section 5).

4.1 Benchmarking Approach Used

Benchmarking is generally described as the process of comparing a process, processes or performance metrics for, in this case, a project that wants to achieve a successful outcome, to industry best projects or approaches that have achieved a successful outcome. The parameters that are selected for benchmarking are the items or values typically measured and compared against the quality of results, time taken, schedule adhered to and cost. In Section 3 we identified five risk parameters, each of which is affected by the tunnel length for the reasons described previously. We have completed a benchmarking exercise for tunnel length and ventilation.

We built a database of projects based on tunnels of a similar nature to the TTT - tunnels excavated in soft ground or soft rock using slurry, EPB or double shield TBM.

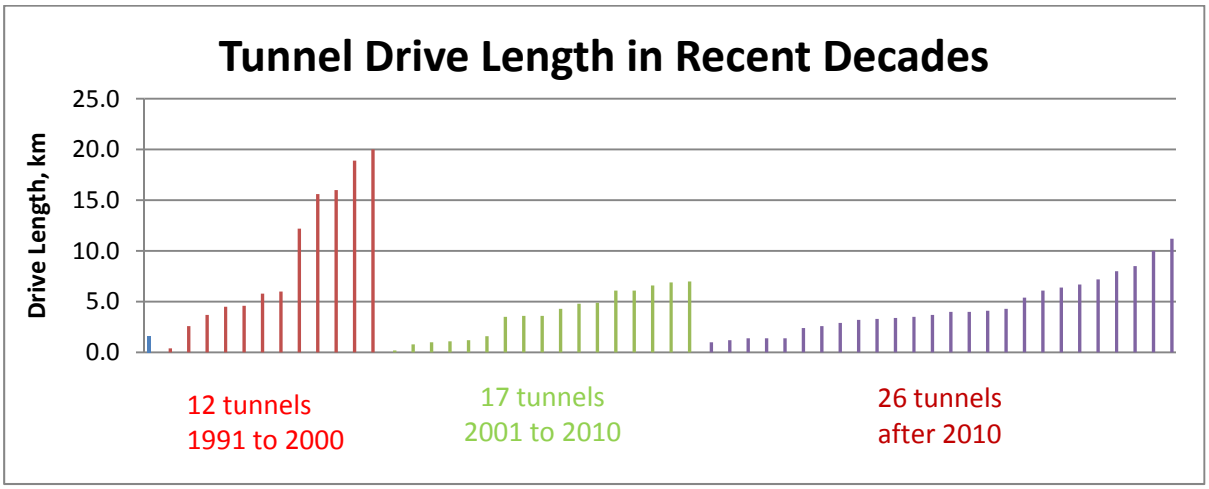
The results of our research of published data are presented in Appendix A. Further details on the compilation of the database and the sources searched can be found in Appendix B.

4.2 Results of Benchmarking

4.2.1 Benchmarking Tunnel Drive Length

The database we developed from published data is limited to size and drive lengths of soft ground tunnels. The results of our research of published data are presented in Appendix A. This research found a total of 55 tunnels driven in soft ground or soft rock under high pressures using a closed face TBM constructed since 1991. The tunnel drive lengths ranged from 0.2 km to 20 km in length. The two longest tunnels with regards to single drive length were two of the Channel tunnels completed in 1991. These tunnels had lengths of 18.9 and 20.0 km and were driven in Chalk. As shown on Figure 4 the majority of tunnels have a drive length of 4 to 6km. Also the number of tunnels with drive lengths in excess of 5 km has increased in each of the last three 10- year periods. The number of tunnels exceeding the preferred scheme's maximum drive length of 7.68km drive length (Kirtling Street to Chambers Wharf) is exceeded by nine tunnels including two of the Channel Tunnels. In the database five tunnel drives exceeded the 11.95km length that would be required for Alternative A and seven drive lengths exceed the 7.2 km length required for Alternative B.

Figure 4: Summary of Soft Ground Tunnel Drive Length



In our database the tunnel diameters ranged 2,500 mm to 17,500 mm. The largest soft ground tunnel is the Seattle transportation tunnel currently under construction under the City of Seattle Washington and presently holds the record for the largest diameter soft ground TBM. Many of the larger diameter tunnels in our database represent transportation tunnels and generally those tunnels when in soft ground have shorter drive lengths than the proposed tunnel segments for this project.

4.2.2 Benchmarking Ventilation Issues

The ventilation requirements during construction do not significantly vary because of the tunnelling medium. These longer drives do show that ventilation issues during construction have been encountered before and contractors have developed acceptable ways of addressing this issue for long tunnel drives.

4.3 Discussion of Identified Risks Based on Results of Benchmarking

The following discussion of risk associated with the alternatives is based on our review of the present TTT project as presented in the documents listed in Section 1 assessed using the results of the benchmarking exercise and our professional experience and opinions. The planned project like all major civil projects involving tunnelling underground has inherent risks. There are unique risks associated with tunnelling. The consequences to cost and schedule of risks that we have identified due to two alternatives are judged in comparison to the impact these same risk parameters can have on the preferred scheme.

Normally in tunnelling projects, the most significant risk to budget and schedule is the selection of the correct TBM. This risk is true for any tunnel project but the magnitude of the consequences of an incorrect TBM selection increase as the drive length increases. In the case of the TTT, the tunnelling media between Acton Storm Tanks and Kirtling Street is expected to be relatively uniform. In addition the preferred scheme expects that an EPB TBM will be used for both for the drive from Kirtling Street to Carnwath Road, and from Carnwath Road to Acton Storm Tanks. The risk associated with the tunnel drive segment for Alternative A therefore is not expected to be affected by the risk of TBM selection. The uniformity of the expected tunnelling media along this drive segment is very conducive to using the preferred scheme EPB TBM. As a result the risk of correct TBM choice has not been used as a parameter in our risk model. A discussion on potential use of Hybrid EPB/Slurry TBMs has been included for information in Appendix E for reference.

4.3.1 Hydrostatic Pressure and Maintaining Face Stability

Assuming that the tunnel depth does not change substantially from the profile presented in the drawings of the Preferred Scheme Plan the tunnel will be driven under as much as 10 m depth of open water. The overburden thickness from the bed of the Thames estuary to tunnel crown is 23 m or more. Most of the tunnel from the Acton Storm Tanks to Kirtling Street is in the London Clay. Based on these depths, if probing ahead to find safe havens for tunnel inspections can be found, minimal to no compressed air would be required for intervention inspections (see Appendix C). For the given TBM size the machine has the room to provide a decompression chamber at the tunnel heading for safety. This risk is not considered to be any different for either Alternative A or B than the preferred scheme and as such is not included in the assessment.

4.3.2 Maintaining Tunnel Alignment and Grade

Tunnel survey is a multi step process. First the surveyor lays out the alignment on the surface and establishes benchmarks near the shaft locations. The next step is transferring the bench mark locations to the bottom of the launch shaft. This step is typically the most difficult and it is critical that it is performed correctly. An accurate way is to use a gyrotheodolite.

As the tunnel advances the survey control points have to move along with and behind the TBM. Most TBM guidance system require a fixed point attached to the tunnel wall where the survey equipment is located. This fixed point must be relocated as the advance continues. Each time this is performed it increases the chance of compounding any previous errors.

Mitigation of this risk is a contractor responsibility typically addressed by using experienced surveyors familiar enough with their methods so that they can advance the survey accurately for several miles even if the tunnel alignment contains curves. As an example CDM Smith was involved in the Chattahoochee tunnel project (Georgia, USA) which was about 5 miles with several curves. (This project was in hard rock and therefore not listed in the database.) On that project a guidance system that incorporated a gyrotheodolite to mitigate survey errors was used. As discussed in Section B.2, the lesson learned in one of the WTP-4 Tunnels of the Jollyville project, which was a straight tunnel alignment, was that it was performed using less sophisticated techniques for both the survey itself and for monitoring the TBM performance and errors did occur.

At present new systems that reduce the required survey time and increase accuracy are being developed. This risk is considered to be manageable during construction so that it should be considered a very low risk of occurrence.

4.3.3 Risk Items Associated with Alternative A - Elimination of Carnwath Road Riverside Shaft

This alternative extends the length of the tunnel drive from the Kirtling Shaft to the Acton Storm Tanks. This is a drive of approximately 11.95km. The tunnel ID for this drive will be 7,200mm. The risk issues are an increase in tunnel drive length of 4.27km over the current proposed longest drive length of 7.68km (Kirtling Street to Chambers Wharf) and a reduction in the clearances of the Lee Water Tunnel and NG cable tunnel by about 500mm.

Abrasive wear to the TBM can be addressed by use of different types of soil conditioners to reduce the wear and subsequent need for more frequent repair interventions and reduction in advancement rates.

We would expect that maintenance to the face of the machine would be under compressed air. Working in those conditions can be estimated with regards to time and cost impact. The longer the tunnel drive the more frequent are the maintenance inspections and modifications or replacement of cutters should be expected. These estimates are made and used in the @Risk model presented in Section 5.

Ventilation of the tunnel during construction will be required. Details of the method of circulating air in the most efficient manner are both design and construction means and methods that have to be addressed. This system is designed and maintained by the contractor as part of the means and methods of construction. Normally a Contractor will ventilate the tunnel during construction using a ventilation system powered from the main tunnel drive site. An increase in tunnel length requires that the overall ventilation conduit system may be increased in size or additional in-line booster pumps are installed in the conduit to provide the necessary air circulation. It is noted that for a longer drive length, the Contractor also has the possibility of using intermediate shafts (in this case CSO site shafts) for ventilation purposes.

Maintenance issues with the tunnel require mean routine inspections (usually once every 10-year period) and maintenance cleaning and repairs as needed. Today the inspections can be done using robotics in the form of torpedo shaped submersibles that can be controlled remotely to video the entire tunnel lining and also track the location of the submersible from shaft to shaft. The TTT is designed for one air exchange per day. Sewer inspections are never performed with man-entry without personal protective equipment for Confined Space Entry, regardless of the design rate of ventilation for the tunnel. During man-entry operations, personnel are equipped with personal air supplies and air monitoring equipment, in addition to being tethered to a manned rescue tripod at the surface. Prior to any entry personnel complete health and safety risk assessments and are must be appropriately training. Safety procedures for such operations have redundancy - that is should one safety mechanism fail, another backup option is available. Should a condition be discovered during an inspection that requires man-entry maintenance then Confined Space Entry health and safety procedures would be followed. Such maintenance repairs are not considered as a change in cost or schedule to the project.

The preferred scheme air management plan indicates that the empty tunnel would operate at one air exchange per day under the low flow air rate scheme and that the tunnel is proposed to be actively ventilated at Carnwath Road Riverside and Abbey Mills Pumping Station. We propose that the Carnwath Road Riverside ventilation system could, under Alternative A, be relocated to the Acton Storm Tanks site and in that way the tunnel could be ventilated at its extremities (see Section 6.2.9 for more details).

4.3.4 Risk Items Associated with Alternative B: Phase 1 Drive Strategy including Barn Elms as drive site in lieu of Carnwath Road Riverside Shaft

This alternative consists of using the 15 hectare Barn Elms site in-lieu of the Carnwath Road Riverside site. We assumed that the ventilation system to be part of the facilities at Carnwath Road would be part of Barn Elms infrastructure. Using this site would increase the tunnel drive length from 5.0km to 7.2km. This drive length increase is a risk similar to the one detailed for Alternative A; however, the risk of occurrence are in proportion to the drive length. Therefore while this is an increase in risk in comparison to the preferred scheme it is less than the one presented for the longer drive alternative.

Similarly the ventilation issues both during construction and for tunnel maintenance requirements represent the same risk issues with increase in cost relative to the preferred scheme but less than the Alternative A.

Section 5 Risk Assessment

This section presents our approach to the risk assessment conducted for this study, documents the results and presents our opinion of the risks to the project between Kirtling Street Shaft and the Acton Storm Tanks if Alternative A or B as presented in Section 3 are implemented. The change in terms of project schedule and cost are in comparison to the preferred scheme. To arrive at these assessments it was necessary to apply probability factors to various parameters. The process we used to develop and assign those parameter values for Alternative A and Alternative B and the results of these analyses are summarized in this section of the report.

Risks presented in Section 3 are discussed in the following text in terms of the technical issues that cause risk, our approach to making evaluation of parameters used to quantify the risk in terms of budget and schedule impact and the results of those evaluations.

Only those risks that were anticipated to be different in the preferred scheme compared to Alternative A and/or B were used in the model. As such two model versions were created one for each of Alternative A and Alternative B.

5.1 Input Values for Risk Assessments

Using the process described in Section 4 to develop a database we assessed the occurrence probability (frequency and consequence) of risks associated with Alternatives A and B. The @RISK software allows different probability distributions for each identified risk. In this analysis the selected distribution shape, frequency of occurrence, consequence to budget and consequence to schedule inputs are presented in Table 2. Details of this process are presented below in this section.

Table 4: Variable Risks included in @Risk Models for both Alternative A and Alternative B

Variable Risk	Risk Distributions Used for Variable	Frequency of Occurrence	Consequence of occurrence - Schedule (Probability Distribution Used)	Consequence of occurrence - Budget
Number of Interventions required for inspection increases with increasing tunnel length	Lognormal	Assume 1 per 75m for 7-10km, and 1 per 150m for 10 - 12km	Each event will be 1 day and could go as high as 4 days (PERT distribution)	Delay time at hourly rate for main tunnel by Lot #
Number of Interventions required for maintenance increases with increasing tunnel length	Lognormal	500 m from 6 to 9 km 400 m from 9 to 12 km	Each event is 2 days and upper limit is 1 wk (PERT distribution)	Delay time at hourly rate for main tunnel by Lot #
Risk of TBM failure (Only included Alternative A due to significantly longer drive over preferred scheme. In Alternative B the longest drive is only 250m longer than preferred scheme)	Binomial	3% Extra chance of failure	2 to 12 months (Triangle Distribution)	£2 million plus labor charge (Triangle Distribution)
General advancement rate - risk of reduction in progress due to wear on TBM and increased travel time to face	Lognormal	Assume max different reduction 100m/wk to 95m/wk	From 100m/wk to 95m/wk (Lognormal)	Hourly crew rate

Additional variables included in the Alternative A model include:

- **Carnwath Road Shaft no longer needs to be constructed** - the consequence on cost saving was included as part of the cost difference assessment - this includes not having to construct the shaft, and not having to purchase or mobilise the smaller diameter (6.5mID) TBM. In terms of impact to schedule - the schedule savings from not constructing the shaft and not mobilising the second TBM are not included in the assessment as they are not deemed to be on the critical path);

- **Loss of ability to drive concurrent tunnels -** there is not deemed to be any cost impact due to the loss of concurrent tunnels apart from possible low costs related to mobilising a second tunnelling crew, as such no cost consequence for this variable has been considered. This issue is the single greatest issue affecting schedule as in driving one 11.95km long tunnel, the ability to drive 5km of tunnel at the programmed rate of 100m/week is lost. This time impact has been included in the model.

Additional variables included in the Alternative B model include:

- **Removal of Barn Elms CSO Shaft and connector tunnel from Contract -** In Alternative B the tunnel would be relocated to pass through Barn Elms as such there would be no need for the construction of the Barn Elms CSO Shaft or connector tunnel that could be replaced by use of the Barn Elms main drive shaft. It is further noted that it is assumed that all costs in the contract covering the Carnwath Road shaft would cover the construction of the Barn Elms shaft.

These risk parameter values (frequency of occurrence) were input into the @Risk model which provides output in terms of probable impact to schedule and budget based on the input values for consequence of occurrence for schedule and budget (see Table 4). Some additional information on values chosen for consequence of occurrence for budget and schedule are presented below.

Consequence of occurrence - Budget

The @RISK software allows output of a base cost and the plus/minus range based on the confidence level that is desired. The input we used for evaluating each risk item was based on the range in project cost presented by Thames Water in their OJEU notice (OJEU, July 2013) for each of the three Contract Lots (see Table 5).

Table 5: Contract Lot estimated sizes (Thames Water OJEU Notice, July 2013)

Lot	Contract Name	Estimated Range (£M)
Lot 1	C405 Thames Tideway Tunnel - Main Works - West	300 - 500
Lot 2	C410 Thames Tideway Tunnel - Main Works - Central	600 - 950
Lot 3	C415 Thames Tideway Tunnel - Main Works - East	500 - 800
Total		1400 - 2250

The schedule for the different identified contract lots was estimated from the schedules presented in each of the Thames Water Planning Assessment Appendix documents (Thames Water (Doc Ref.: 7.01), January 2013) converted to working hours. The identified elements in each of the Lots were broken down into four categories representing major work elements:

- Main tunnels;
- Collector tunnels;
- Large diameter shafts; and;
- Small diameter shafts.

We performed calculations to estimate a unit cost for the main tunnels by first separating the tunnels in each Contract Lot into our two tunnel categories; main or collector. Shafts with inside diameters less than 12 m were considered 'small diameter shafts' and shafts equal to or greater than 12 m were considered 'large diameter shafts'.

For each Contract Lot the total volume of excavation was calculated based on the inside diameter of the tunnel as presented in the preferred scheme plus an additional estimated increase in the diameter to reflect the actual outer excavated area necessary to excavate the tunnel and install the liner . For tunnels an additional 1.8m was added to the diameter to account for the lining thickness (2-pass lining system with total thickness of 65cm and TBM size (TBM shield thickness and overcut for steering, 50 cm) bored diameter. For shafts an additional 2 m was added to the inside diameter to account for the slurry wall thickness. For all excavation in soil we used a bulking factor (expansion of the soil volume from in-situ to spoil train) of 30%. The range in cost for each Lot was then proportioned as a ratio of the element volume to the entire volume of the Lot. This cost was then divided by the hours estimated for the construction of the element to determine a unit cost (£/hour). This unit rate was used to calculate the impact cost for each risk contingency occurring.

It should be noted that estimating costs in this manner is for order of magnitude and comparison of alternatives. A refined output would be possible if further cost information were available.

Consequence of occurrence - Schedule

It should be noted that the schedule for the TTT is complex with numerous main tunnel drive site shaft commencing prior to the main tunnel reception sites being completed, and CSO connection tunnels programmed to be completed after the main tunnel has driven past the connection point. The @Risk model only considers scheduling impacts expected to affect the critical path.

5.2 Alternative A - Elimination of Carnwath Road Riverside Site

5.2.1 Risk due to Increased Tunnelling Length

The longest drive length in the preferred scheme is from Kirtling to Chambers Wharf - a distance of 7.67 km. The alternative of driving the a tunnel from Kirtling to Acton Storm Tanks site results in a tunnel length of 11.95km.

As we have shown in the benchmarking of tunnel drive lengths in soft ground tunnels, drive lengths in excess of 11.95km have been completed in five of the 55 projects cited in this report. There are several more tunnels that exceed this drive length but those were excavated in hard rock. Those were not considered in this evaluation. The risk issues associated with long soft ground tunnel drives deal mainly with elements that are only subjectively quantified such as machine wear or safety issues such as the level of risk associated with need for emergency event requiring tunnel egress. There are other concerns with a long drive length such as haul time from shaft to tunnel heading and ventilation requirements. Similar to previously constructed hard rock tunnels these are conditions that can be quantified and the costs associated with these activities can be accounted for in the design and bid.

There has been significant recent technological advancement in the application of conditioners added to the soil during tunnel advancement that homogenize the soil and reduce abrasion on the cutters. Similar technological advancement has been made with the cutters themselves and the machine designs to excavate the soil and also be able to handle boulders. The magnitude of risk and consequence of occurrence that has to be judged is based on soil abrasion parameters that unfortunately are not standardized at this time. Therefore the cost associated with a risk is a function of how well the parameters can be defined in

the contract documents and how the ownership of the risk is delegated between owner and contractor. This effort is performed during the engineering and construction phases and cannot be addressed here at this stage of the project.

The spacing of interventions along any one tunnel drive should be a function of the anticipated abrasiveness of the soil and other factors that the contractor needs to take into consideration. Our experience on the Brightwater Project indicates that there was less wear on the EPB machines in comparison to the Slurry TBMs. We also concluded that dense silty fine to medium sand (composed of mostly quartz and feldspar) was more abrasive than the clay.

Our review of the Brightwater data indicates that a percentage of the difference in cutter wear rate was probably due to the power applied to the face to excavate the soil (operator controlled). We would also expect that a longer tunnel drive length would warrant closer intervention spacing as the heading is advanced and have accounted for closer spacing of inspections. The down-times associated with these inspections reduces the average advancement rate of the TBM.

Supporting the ground by using compressed air or modifying the ground to strengthen it and reduce permeability have all been done very successfully in the past to perform interventions.

5.2.2 Risk of Insufficient Clearance to Infrastructure adjacent to Tunnel Heading

We reviewed the technical paper “Bored Tunnelling in the Urban Environment” by Mair and Taylor (1979) that presented data on the horizontal distribution of ground movement as a function of distance from the tunnel. This data consisted of five case histories of tunnels in the London Clay. Four tunnels were shield driven and one was hand mined. All of the tunnels were approximately 4 m in diameter. Based on these empirical relations and taking into account the greatly improved technology in ground control in tunnelling today the 3 m spacing is a good planning level parameter value to use. Because of the ability to control and limit the volume of lost ground during tunnelling the risk of causing extensive damage to existing tunnels using this spacing is considered very small. The risk will increase with closer proximity to existing structures. The larger tunnel diameter that would be used because there is no chance to change TBM with the elimination of the Carnwath Road Riverside shaft reduces means the 7,200 mm ID tunnel is crossing over the Lee Water Tunnel, rather than 6,500mm ID in the preferred scheme.

As presently shown the clearance is assumed to be 3m using the 6,500 mm ID tunnel. This Alternative A reduces the clearance by 0.35m. Much of this risk is mitigated with the ability to control alignment and limit ground loss in tunnelling today. This control allows the contractor to greatly reduce the magnitude of ground movement that occurs within 3m of the tunnel bore in comparison to the movement that was expected at that same distance in the 1970’s. Stated otherwise, the magnitude of ground movement and in-situ stress changes to the soil at the location of the existing infrastructure expected today would correlate to a greater separation between tunnel and infrastructure.

An issue that has to be addressed for this alternative to be viable is the change in grade required to thread between the Lee Water Tunnel and proposed NG Cable tunnel. The necessary change in grade can be achieved during the tunnelling. The rate of change is the same as for a curved section. To maintain the same invert elevations as shown on the Preferred Scheme the tunnel slope has to be 0.00195. This gradient is achievable without significant cost or schedule impact to the tunnel mucking operations. The hydraulics would need to be checked but it is not likely that it is a significant change.

5.2.3 Risk of Longer Contract Duration

See Section 6 for discussion

5.2.4 Risk of Ventilation Issues

See Section 6 for discussion

5.2.5 Risk of Safe Egress

The risk issue with regards to the need for emergency access and/or egress from a tunnel needs to be considered in the evaluation of these alternatives. Should a medical emergency occur at the heading then travel time has to be evaluated as a risk. This risk issue can be mitigated by providing medical emergency equipment in the tunnel during construction.

5.3 Risk Findings – Elimination of Carnwath Road Riverside Shaft Site

As indicated in Table 5, the preferred scheme is expected to cost between £1.4bn and £2.3bn, with most likely cost of £1.6bn being used generally in relation to this project. For Alternative A the potential change to the budget is expected to be minimal in the order of ±2%. The predominant reason for this cost impact is the significant cost savings from removing a shaft from the Contract and in addition removing the requirement to purchase and mobilise a costly second TBM. The impact to the schedule is more significant with these risks over 12 months as estimated in the model. The principal reason for the schedule impact is the removal of the possibility to drive two separate tunnels in the preferred scheme concurrently.

5.3.1 Cost

The predominant reason for this cost impact is the significant cost savings from removing a shaft from the Contract and in addition removing the requirement to purchase and mobilise a costly second TBM for the 6.5m ID tunnel.

5.3.2 Schedule

For Alternative A in terms of impact on schedule the largest impact is that construction of the Carnwath Road – Acton Storm Tanks, and Kirtling Street – Carnwath Road drives can no longer be simultaneous. This is 5km that will no longer be concurrent which at 100m/week of progress as intended per the TTT preferred scheme, this is broadly a 50 week delay however mitigation measures are possible. It should be noted that the most significant possible mitigation to schedule is the use of a single pass lining system, rather than the two-pass lining system proposed in the preferred scheme (see Section 6.2.1 for further details)).

The 11.95km tunnel can be driven in one of two directions;

1) **Drive Acton to Kirtling Street** – the shaft can be started in Acton Storm Tanks at the same time as the construction of the shaft in Kirtling Street commences. This is a risk as generally contractors prefer to commence a tunnel only after the exit shaft is complete, however this risk is in line with those planned to be taken by the preferred scheme. This option adds additional traffic movement to the Acton Storm Tanks Site due to the requirement for land movement of spoil which up to now had been intended to be removed by sea (from Carnwath Road). Acton to Kirtling drive would be down gradient. This can be done and is done often, but it does require additional internal pumping of construction water to the shaft and adds a risk if these pumps fail.

2) **Drive Kirtling Street to Acton** – Again simultaneous shaft construction at Kirtling Street and Acton Storm tanks, the two TBMs can then leave Kirtling Street firstly heading towards Acton, secondly towards Chambers Wharf. Two sets of spoil would be coming out of the Kirtling Street site although since the rate of tunneling is the same as currently planned – this should not overwhelm that site. This option increases the duration of construction activity at Kirtling Street. This option would be up gradient tunneling - this allows the construction water at the heading to flow by gravity to the shaft

and then be pumped out. The Contract size and potential conflicts at Kirtling Street of this option increases the risk associated with contract size and schedule delays. These can be mitigated by creating two contracts driving both the Kirtling Street to Chambers Wharf tunnel and the Kirtling Street to Acton Storm tanks. Further mitigation to avoid conflicts with two contractors working at the same shaft site could be achieved by changing the direction of the tunnel drives so that Kirtling Street serves as both a working shaft and retrieval shaft for the respective contracts and controlling milestone dates in these contracts.

5.4 Alternative B - Barn Elms Site in-lieu of Carnwath Road Riverside Shaft Site

5.4.1 Risk due to Increased Tunneling Length

This alternative of driving the second tunnel from Kirtling to Barn Elms site is 7.2 km.

As we have shown in the benchmarking of tunnel drive lengths in soft ground tunnels drive lengths in excess of 7.2 km have been done in 10 of the 55 projects cited in this report and is less than the drive length of the first tunnel from Kirtling to Chamber Wharf shaft (7.67km). It should again be noted that Thames Water found both Barn Elms and Carnwath Road Riverside to be suitable drive shaft sites, however ultimately the Carnwath Road Riverside was chosen. The reasons for the selection are presented in the Thames Water Phase II Scheme Development Report (Thames Water, 2011).

The risk issues associated with the elimination of the Carnwath Road Riverside shaft (Alternative A) are the same for this alternative. However the probability of risk occurrence is less because the drive length is shorter in Alternative B.

The risk issue with regards to the need for emergency access and/or egress from a tunnel is about the same as the Kirtling- Chamber Wharf drive in the Preferred Scheme due to the similar drive lengths and there are means of mitigation of medical emergencies with minimal cost.

The spacing of interventions along this drive assumes the same frequency as the preferred scheme has for the long drive between Kirtling and Chambers Wharf which is a slightly longer drive length.

5.4.2 Risk of Insufficient Clearance to Infrastructure Adjacent to Tunnel Heading

The issues are the same for this alternative, as are the probability of risk occurrence, to the preferred scheme since the longer tunnel drive is not a factor at the location of the Lee Water Tunnel crossing.

5.4.3 Risk of Longer Contract Duration

See Section 6 for discussion

5.4.4 Risk of Ventilation Issues

See Section 6 for discussion

5.4.5 Risk of Safe Egress

The risk issue with regards to the need for emergency access and/or egress from a tunnel is not particularly different in Alternative B than in the preferred scheme.

5.5 Risk Findings – Barn Elms Site in-lieu of Carnwath Road Riverside Shaft Site

As indicated in Table 5, the preferred scheme is expected to cost between £1.4bn and £2.3bn, with most likely cost of £1.6bn being used generally in relation to this project. We used the same approach in considering the impacts to schedule and budget for the Alternative B which substitutes the Barn Elms site for the Carnwath Road Riverside site. There is no calculated significant impact to the cost or schedule.

5.5.1 Cost

It should be noted that post Phase 1 consultation on the TTT, when TW decided to selected Carnwath Road over the Barn Elms site, they noted a number of cost and schedule impacts they felt were likely to be more costly, and have a longer duration if Barn Elms was selected over Carnwath Road. With limited data it is difficult to include a cost or schedule impact of the below items and as such they have not been included in the model;

- Carnwath Road "has better river access via the existing safeguarded wharf than is available at Barn Elms. This allows much larger barges (800t – 1000t rather than 350t) to be used to remove excavated materials and deliver construction materials to site. Use of larger barges also has associated cost and environmental benefits"
- At Carnwath Road "Enabling works can also be progressed more easily, especially as there is an existing energy supply on site"
- Carnwath Road "has a higher resale land value, while the Barn Elms site has higher site set-up cost and no resale value."

Section 6 Conclusions to Evaluated Alternatives and Opinion of Stated Concerns

6.1 Conclusions

Based on our research of both public documents and in-house projects and interviews with TBM contractors, our basic conclusion is that the extended tunnel drive length to a total of 11.95 km is technically feasible. There are some added risks to the project that have been identified in this study concerning tool wear and ventilation as they affect the longer tunnel drive. These risks can be managed and mitigated to acceptable levels without excessive cost.

The increased capacity of the ventilation system due to the longer drive length is a given condition that has to be addressed in both the design and construction. With regards to this study risks associated with the ventilation requirements raised by the longer tunnel drive length can be defined and mitigated to an acceptable level with well-defined cost to mitigate.

The issues associated with machine tool wear are much less quantified in the tunnelling industry at this time. Consequently, budget and schedule impacts associated with this risk are not well defined. Good evidence is provided by the Brightwater project (see Appendix B). In that project soil abrasion stopped the original slurry TBM, whereas the EPB TBM used to complete the tunnel did not even require cutter changes for the 3 km of tunnelling to connect with the stuck TBM.

The potential cost and schedule impacts of Alternative A and B are presented in Table 6.

Table 6: Summary of Risk Consequences

Alternative	Impact to Budget	Impact to Schedule
A -Elimination of Carnwath Road Riverside Shaft	± 2% Preferred Scheme	Over 1 year addition to the critical path (it is noted however that significant schedule savings could be made by using a single-pass lining system rather than the proposed two-pass system).
B - Barn Elms Site used in lieu of Carnwath Road Riverside for shaft	No significant impact*	No significant impact

*See Section 5 for costs not included in the Alternative B assessment

These impacts to budget and schedule are relative to the average budget range and a calculated schedule based on tunnel and shaft construction rates for the Preferred Scheme as detailed in the OJEU notice dated July2013.

There is no accepted standard to measure abrasion wear in soil. The abrasion-caused wear rate appears to vary as a function of applied power by the TBM to the soil. Contractors use soil conditioners to reduce the wear but consider this action as proprietary and do not want to publish their approach to mitigation of the wear issue. The approach they use for interventions vary also and often require some form of ground modification to provide a stable and safe environment for the tunnel crew to perform their inspections and maintenance duties on the TBM. The most common ground modification for an intervention is compressed air. Other techniques such as grouting or ground freezing have been successfully used also. As a result we have identified information on interventions on the articles where the information is presented but have not specifically benchmarked this parameter. The ability to monitor the behaviour of the TBM is a major means of mitigating risks associated with issues that arise with soil abrasion..

6.2 Opinion of Stated Concerns

At the start of this study several criteria were raised for assessment against Alternative A and B. These criteria as presented by CDM Smith and in part based on TW concerns were identified in Section 1. With our tunnel design experience we have encountered these same concerns on several projects and have provided our expert opinion based on the limited information we presently have and our understanding ofthe project. The summary of findings for Alternative A and B are presented in Table 7 and Table 8. Further opinion on the stated concern has been included in the following sections.

Table 7: Summary of Findings for Alternative A drive strategy in comparison with the Preferred Scheme

Stated Concern	Comparative Criteria from Preferred Scheme	Alternative A
Schedule	Approx. 6 years proposed by Thames Water (schedule from 2016 - 2023)	Over 1 year addition to the critical path (it is noted however that significant schedule savings could be made by using a single-pass lining system rather than the proposed two-pass system).
Budget	1.6bn (Range of costs between £1.4bn - £2.25bn proposed by Thames Water)	± 2% Preferred Scheme
Impact on contract size for tender	Three Contract Lots with maximum size of any one Lot estimated at £950M	No significant difference to preferred scheme (however would require a reorganization of contract structure/Lots)
Impact on safety due to drive length	Risks associated with safety are always taken very seriously by the industry and are mitigated to the extent possible.	Additional Health and Safety risks include greater travel times to egress points. It is our opinion that with proper precautions and good tunnelling workmanship increased risks can be mitigated to level of a very slight risk.
Avoidance or impact to existing infrastructure	Issue relates to clearance over the Lee Valley Raw Water Main and under the proposed National Grid Wimbledon to Kensal Grid Cable Tunnel. It is unclear the full extent of tunnel clearance that is intended to be achieved however assume 3m (which is the stated minimum clearance)	Despite increased tunnel diameter in Alternative A, it is our opinion that with proper precautions and good tunnelling workmanship crossing under and over these obstacles can be achieved with little to no impact to the in place structure. Significantly closer clearances have been performed without damage to the existing infrastructure
Risk Contingency applied by contractors as a function of tunnel length	This is a risk that is dependent upon the distribution of risk as stated in the contract documents	Additional risk is very manageable as this tunnel drive length has been achieved several times in the industry
Stakeholders	Stakeholder impact on the preferred scheme which would be impacted by Alternative A relates to Stakeholders at the three main Shafts involved Acton Storm Tanks, Carnwath Road and Kirtling Street.	Less risk at Carnwath Road because of the elimination of the shaft, possible increase in risk at Acton Storm Tanks/Kirtling Street
Long term maintenance and worker safety	Criteria related to Alternative A over preferred scheme relates primarily to longer tunnel for egress, and issues related to maintain access.	Minimal increase that can be mitigated
Long term ventilation strategy	For Alternative A this issue relates to the removal of Carnwath Road as the principal active ventilation site for the Thames Tideway Tunnel.	Minimal increase that can be mitigated

Table 8: Summary of Findings for Alternative B drive strategy in comparison with the Preferred Scheme

Stated Concern	Comparative Criteria from Preferred Scheme	Alternative B
Schedule	Approx. 6 years proposed by Thames Water	Very small if any Impact
Budget	1.6bn (Range of costs between £1.4bn - 2.2.5bn proposed by Thames Water)	Very small if any Impact
Impact on contract size for tender	Three Contract Lots with maximum size of any one Lot estimated at £950M	Very small if any Impact
Impact on safety due to drive length	Risks associated with safety are always taken very seriously by the industry and are mitigated to the extent possible.	Very small if any Impact
Avoidance or impact to existing infrastructure	Issue relates to clearance over the Lee Valley Raw Water Main and under the proposed National Grid Wimbledon to Kensal Grid Cable Tunnel. It is unclear the full extent of tunnel clearance that is intended to be achieved however assume 3m (which is the stated minimum clearance)	No increased Impact
Risk Contingency applied by contractors as a function of tunnel length	This is a risk that is dependent upon the distribution of risk as stated in the contract documents	This length is shorter than the longest proposed drive in the preferred scheme (Kirtling Street to Chambers Wharf) and in more consistent ground therefore there is no increase in risk
Stakeholders	Stakeholder impact on the preferred scheme which would be impacted by Alternative B relates to Stakeholders at Barn Elms.	Risk will be associated to Barn Elms stakeholders whom were strongly opposed to the Phase 1 proposal which included a main tunnel drive site at Barn Elms.
Long term maintenance and worker safety	Criteria related to Alternative B over preferred scheme relates primarily to a 250m longer tunnel for egress, and issues related to maintain access.	No significant increase - can be mitigated
Long term ventilation strategy	For Alternative B this issue relates to the use of removal of Barn Elms as the principal active ventilation site for the Thames Tideway Tunnel.	No significant increase

*See Section 5 for costs not included in the Alternative B assessment

6.2.1 Schedule

The schedule risk associated with the alternatives has been presented in Section 5.

It is our opinion that the various parameter values used to develop the schedule are reasonable. The effect on the schedule should be continued to be evaluated as the design develops. This on-going evaluation of the schedule should take into account the variability of several different parameters so that a realistic range of time to complete any one element and all the elements can be linked is developed in order to best account for unknowns and make use of the risk evaluation process.

A major risk consideration for this entire project is meeting the overall schedule. In our review of the Engineering Design Statement it was observed that the present scheme is to construct this entire tunnel system as a two-pass system consisting of precast segmental lining with a second pass of spray concrete. Many CSO projects in the USA have been designed and constructed using a one-pass segmental lining often with international tunnelling design firms and contractors involved with both design and construction. Using a one-pass system would have a significant reduction on the overall schedule. In a one-pass system, recesses in the liner segments for bolting and other small openings needed for construction can be grouted. The design of the hydraulics in conveyance tunnels typically includes consideration of how the roughness coefficient will change as the structure ages during its design life and in between maintenance periods. It's

been CDM Smith's experience that 'self cleansing' properties of the tunnel are often determined by the Owner and also include consideration for debris and grit management approach. It is beyond the scope of this report to consider this in detail; however, the impact to cost and schedule makes this worthy of further consideration.

There are risks involved with having two contracts working in the same site or shaft. This risk involves work-space conflicts that result in delays to both contracts. Mitigation of this type of risk can be addressed to a large extent in design by either staggering the construction schedules to avoid the conflict or by redesign of the shaft to a "figure 8" configuration (see Figure 5) to allow both contractors to work in one part of the shaft. In consideration of Alternative B, if the Barn Elms site is used as a main tunnel construction site (drive and reception), then work on that shaft and construction of the Barn Elms to Acton Storm tanks tunnel could be performed concurrently with tunnel related work from Kirtling Street to Barn Elms. This approach reduces the risk of a schedule interference conflict at the Barn Elms site in comparison the preferred scheme. Under the preferred scheme tunnelling from Kirtling Street to Carnwath Road, 5.0 km, and tunnelling from Carnwath Road to Acton Storm tanks, 6.95km start within a few months of each other. There is a potential schedule conflict at Carnwath Road if the drive to Acton Storm Tanks is not completed prior to the TBM arrival from Kirtling to Carnwath Road drive. Using the Barn Elms site instead of Carnwath Road reduces the drive length to Acton Storm Tanks by about 2.0km and increases the drive length from Kirtling by the same length. These changes in length present a more likely scenario of the drive to Acton Storm Tanks being completed prior to the drive to Barn Elms from Kirtling and thus avoiding the interface conflict at the Barn Elms shaft site.

Figure 5: Use of a "Figure 8" configuration with two contractors operating at same site shaft

A proposed alternative design option would be if one tunnel is driven from Acton Storm Tanks to Barn Elms, with the other tunnel still driven from Kirtling Street to Barn Elms. These two tunnels could both be advanced toward the Barn Elms shaft site as a main tunnel reception site. The advantage of using the Barn Elms site as a receiving shaft for both tunnel headings is that it reduces the time both contracts require at this main tunnel reception site to complete their respective work of removing their TBM. A similar approach was used for the Brightwater West and Central contracts where both tunnels BT-3 and BT-4 were originally planned to exit at the Ballinger Way shaft (see Appendix B for further details on the Brightwater project).

The alternative shaft design would be similar to the configuration used on Brightwater. In this case the same contractor used two shafts for different headings.

6.2.2 Budget

The budget numbers we used for this study carry a large contingency to account for unknowns. As the design is advanced these unknowns will be researched and explored and parameter values established to account for their impact on cost and schedule. The result will be a smaller contingency. In general the ranges generated using the risk model is in line with what we would expect for this size project and at this level of planning.

Our conclusions regarding budget impact due to the two alternatives are presented in Table 6.

6.2.3 Impact on Contract Size for Tender

The ability of a tunnel construction firm to obtain a Performance Bond is key to getting as many qualified bidders as possible. Contractors will form joint ventures to mitigate their risk. The large national and international tunnelling firms generally have bonding capacity of £125 million. There are mega firms currently performing tunnelling projects in the USA that are over $1 billion as lead contractors without joint venture partners. Other equally large firms operate from SE Asia and other European countries

It is our opinion that these contracts as presently presented in the Preferred Scheme or with the alternatives are within the limits of what contractors will be prepared to bid. The advantage of tendering contracts of this magnitude is that unqualified firms will not submit bids.

Table 9 shows recent tunnelling contracts issued in the UK and Internationally. Whilst in the UK some of the larger contracts currently being carried out are below £600M, internationally contracts greater than £700M have taken place.

Thames Water announced the shortlisting of the tunnelling contractor teams for the three proposed contracts (Thamestidewaytunnel.co.uk, 2013) on the 29th October 2013. Eight contractor teams have been shortlisted the three Contract Lots of which seven were Joint Venture teams made up of two or more contractors. This clearly indicates that there are contractor teams in the market place willing to consider contracts of this size.

It is noted that Alternative A would require a re-organisation of the contract structure/Lots as follows:

Lot 1 - Main tunnel drive including shafts and connections - Acton Storm Tanks to Kirtling Street and long connection drive - Frogmore;

Lot 2 - Main tunnel drive including shafts and connections - Kirtling Street to Chambers Wharf

Lot 3 - Main tunnel drive including shafts and connections - Chambers Wharf to Abbey Mills Pumping Station and long connection tunnel drive - Greenwich Pumping Station to Chambers Wharf.

It is our opinion that these contracts as presently presented in the Preferred Scheme or with the alternatives are within the limits of what contractors will be prepared to bid. The advantage of tendering contracts of this magnitude is that unqualified firms will not submit bids.

Table 9: Recent UK and International Tunnelling Contracts

Package Description	Description	Contract Award Date	Contractor(s)	Team Structure	Cost Range
Example Large Scale UK Tunneling Projects					
C300/ C410 Crossrail Running Tunnels - West;	Royal Oak to Farringdon (6.2 km), Bond Street & Tottenham Court Road Stations - Early Access Shafts & Sprayed Concrete Lining Works	Jan-11	BAM Nuttall Ltd / Ferrovial Agroman (UK) Ltd / Kier Construction Ltd	JV	£400m to £550m
C305 Crossrail Running Tunnels - East	Limmo Peninsula to Farringdon (8.3 km); Limmo Peninsula to Victoria Dock (0.9km); Stepney Green to Pudding Mill Lane (2.7km)	Dec-10	Dragados S.A. / John Sisk & Son (Holdings) Ltd	JV	£400m to £550m
C310 Crossrail Thames Tunnel	Plumstead to North Woolwich (2.6km long and about 15 m below the existing river bed)	Apr-11	Hochtief / J Murphy & Sons Ltd	JV	£100m to £250m
National Grid London Power Tunnel	Hackney and Willesden (via St John's Wood) and Kensal Green and Wimbledon. 32 kilometres of 4.0mID and 3.0mID tunnels, 14 shafts, and four connecting tunnels with associated underground chambers.	Oct-10	Costain/Skanska	Joint Venture	£200M
Lee Tunnel	6.9km, 75m deep, 7.2mID	Jan-10	Morgan Sindall, Vinci Construction and Bachy Soletanche	JV	£417M
Example Large Scale International Tunneling Projects					
Cologne North-South Light Railway, Southern Section, Single Track Metro Line	3,260 m of light railway line with 2 single-track tunnels, total length: 5,400 m, internal diameter: 7.30 m; 7 stations; 1 crossover; 1 weaving section	Nov-03	Wayss & Freytag Ingenieurbau AG in joint venture	JV	€ 470M (£405M)

6.2.4 Impact on Safety due to Drive Length

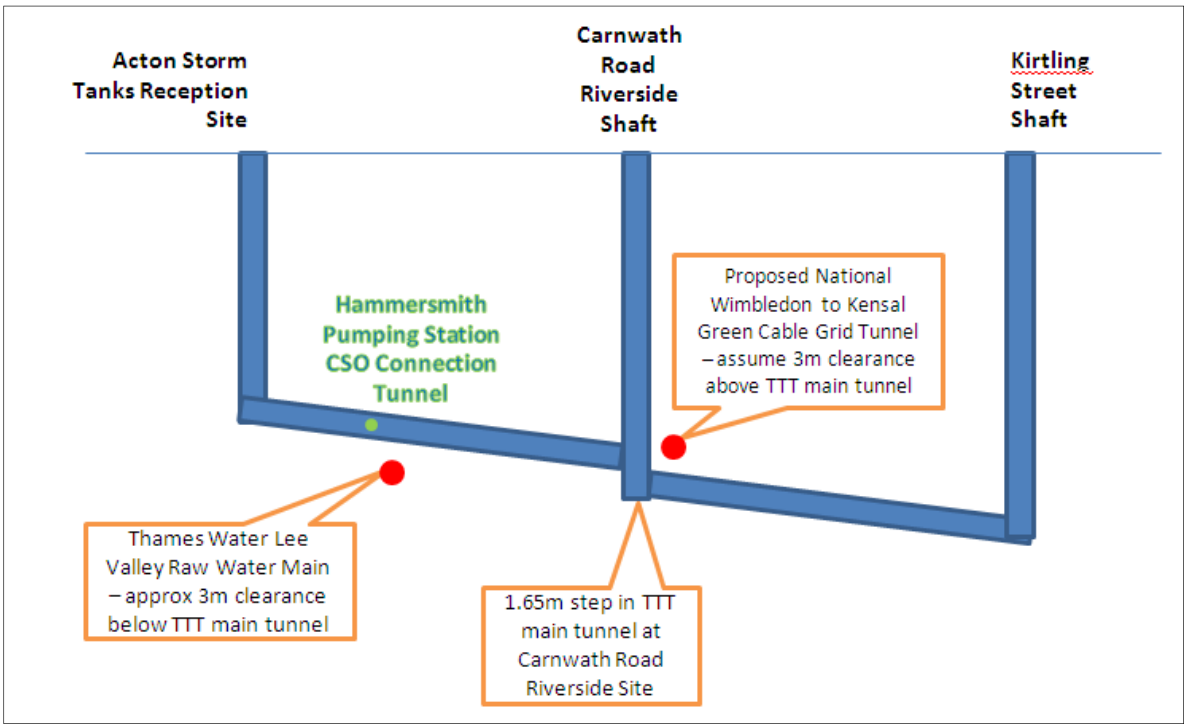
Risks associated with safety are always taken very seriously by the industry and are mitigated to the extent possible. The vast majority of accidents in tunnels are due to human error. A concern of a long tunnel is the time it would take to get a worker to the surface to receive medical attention. This can be mitigated by having medical emergency equipment and properly trained safety staff in the tunnel shaft and heading. This is a common practice.

Contractors are also now beginning to use small vehicles to transport crews from the tunnel heading back to the surface for decompression after hyperbaric interventions. This allows the decompression to occur in a more comfortable chamber.

6.2.5 Avoidance or Impact to Existing Infrastructure

Generally with deep tunnels associated with CSO projects the infrastructure avoidance is limited to existing tunnels and deep foundations. The sequence of which structure is in place first has to be taken into account when evaluating the effect of one structure on another. The 3 m spacing is a little less than a bored tunnel radius clearance which is tight but has been successfully done elsewhere. During design the actual engineering properties of the soils at this vicinity need to be evaluated and the ground modification as needed to achieve a satisfactory safety factor should be developed as part of the contract.

Figure 6: TTT Preferred Scheme Existing Infrastructure Vertical Alignment Factors



The NG Cable tunnel is shown as being over the Tidewater Tunnel once it is in place and therefore should present less of risk of damage to the existing tunnel because it is below the proposed tunnel. Ground movement is more pronounced at and above the springline of the tunnel being excavated

With the controls and ability to monitor TBM and ground behaviour in real time tunnelling it would be expected to be performed with significantly less ground movement than with open face shields. Reduced ground loss would be a major means of mitigating risk of damage to existing infrastructure at either of these crossings.

It is our opinion that with proper precautions and good tunnelling workmanship crossing under and over these obstacles can be achieved with little to no impact to the in place structure in Alternative A.

For Alternative B the possibility to follow the preferred scheme avoidance mechanism of a reduced diameter tunnel between Acton Storm Tanks and Barn Elms, and to create a step change in vertical alignment at the Barn Elms drive shaft mean that there is no impact on this issue over the preferred scheme.

6.2.6 Risk Contingency Applied by Contractors as Function of Tunnel Length

Risk in a contract is generally chosen by the Client to be either carried by the Client; shared with the Contractor; or; should be addressed fully by the Contractor in their contract price. If all risk is given to the Contractor, the bid prices are likely to be higher. This section presents some of the risks that contractors consider when pricing a contract. This issue is not expected to drive any higher cost bids with either Alternative A or B, than the preferred scheme as the bid prices in all cases will be based on how risk is shared in the contract.

The longest distance between construction shafts in the preferred scheme is 7.67 km. Alternative A evaluated in this study would increase that distance to 11.95km (elimination of the Carnwath shaft) and Alternative B (using Barn Elms Site) would increase the drive length of the segment from 5.1km to 7.3km which is slightly less than the preferred scheme's present longest drive length.

Among many factors the risk of a TBM getting stuck will increase with the distance the machine as advanced due to wear on the exposed tools. This risk can be mitigated by providing an accurate interpretation of the ground conditions and tunnelling related parameters so the contractor can adequately design the TBM and its cutters. Further mitigation involves frequent inspections of the TBM condition and constant vigilance of the monitored parameters of specific machine parts during the tunnelling.

Even with these mitigations in place machines get stuck. There are methods to rescue these machines that can be executed entirely from below ground. The primary obstacle that has to be overcome is to develop an approach that allows for tunnel crew to access the machine in a safe environment. A means of achieving this stability with a high degree of confidence is to use ground freezing. Ground freezing has been used to rescue TBM's around the world. In cases in Cairo, Egypt, Istanbul Turkey and Seattle Washington, USA ground freezing was used as the means of providing stable ground. Each of these cases accessed the stuck TBM using a combination of surface and subsurface access only because of the economics. The same access could have been achieved for these projects just working from below ground but with higher cost and longer schedule impacts.

Other methods of achieving ground stability using a combination of permeation grouting and compressed air have also been used successfully. Additional mitigations that have been used are to perform jet grouting of selected zones as safe havens for scheduled maintenance to the TBM. This approach was successfully used by Bouygues for their current project in Miami FL USA.

6.2.7 Stakeholders

The concerns raised by stakeholders are typically with regards to the work activity that they can see or are impacted by such as noise, lights at night or traffic.

The contract documents can address these issues putting limits on work hours, direction that lights have to face, limits on noise. Each of these parameters can have values assigned to them and they can be measured during construction. Actions to mitigate any of these values from exceeding threshold limits can be defined and implemented if the lower limits are met or exceeded to prevent a non-conformance action by the contractor.

The schedule is not expected to increase in Alternative B however in regards to Alternative A, the schedule is expected to increase by over a year due the driving of one long tunnel preventing the scheduling benefits of driving two separate tunnels. Changes such as this would affect stakeholders. In the case of driving from Acton Storm Tanks to Kirtling Street it would require spoil haul traffic at the Acton Storm Tanks site that would be used as a working shaft site. In the preferred scheme, the Acton Storm Tanks shaft is planned as an exit shaft and spoil is removed by barge from Kirtling and Carnwath Road Riverside as presently planned.

In the opposite drive scheme, from Kirtling Street to Acton Storm Tanks, the full impact of the one year delay would be experienced by the stakeholders adjacent to this site.

6.2.8 Long Term Maintenance and Worker Safety

The issues with longer drive distances are: access to the tunnel with large size equipment should major repairs be required; safety of personnel working in the confined space of the tunnel with limited egress locations along the alignment; and cost for inspections.

Access to the tunnel can be achieved by designing and installing a removal cover over a working shaft that would allow for a machine to be lowered into the tunnel of adequate size for either cleaning of the tunnel or to access the entire perimeter of the tunnel. Typically these covers are about the same size as the ID of the tunnel being accessed.

Personnel safety would require a ventilation system. Performing inspections using a remotely controlled camera in a robotic submarine could be used. These systems are presently available and improving all the time. By the time such an inspection is scheduled for the TTT, the equipment available should be able to handle significant distances and provide detailed status of the tunnel condition with limited if any personnel in the tunnel. In 2009, we completed an inspection survey of the 3 km Park River Tunnel in Hartford CT, USA using a robotic submarine to video the entire tunnel length. Accessing the main tunnel through the CSO connection points is also a possibility if the CSO connection points have been designed to allow for that operation.

Assuming a system allowing for remote control inspection of the tunnel is available, the additional cost associated with the longer distance between shafts would be a very minor for Alternative A.

For Alternative B using the Barn Elms site rather than Carnwath Road site is similar to the existing contract and so no significant additional risk or cost.

6.2.9 Long Term Ventilation Strategy

In reviewing the Thames Tideway Tunnel Air Management Plan, we find that the air flow and pressure estimates are absent. However, there is an indication that the empty tunnel would operate at one air exchange per day under the low air flow rate scheme and that the tunnel is proposed to be actively ventilated at Carnwath Road Riverside and Abbey Mills. We would propose that the Carnwath Road Riverside ventilation system could, under Alternative A,be relocated to the Acton Storm Tanks site and in that way the tunnel would be ventilated at its extremities. The profile of the tunnel (Plate 3.3, Thames Water Air Management Plan (Doc Ref: 7.14, January 2013)) indicates that this is not only possible, but advantageous as the tunnel fills.

The empty volume of the tunnel is circa 1,000,000 m3. If exhausted at only one location, the exhaust fan would need to handle 41,666m3/hr. However, since the exhaust would be divided between two fans at the tunnel extremities, we would expect that the fans would each be designed to handle 50% of the flow each. Thus under the low flow scenario, one fan would draw about 21,000 m3/hr of air.

At one air change per day, the air velocity in the preferred scheme Acton Storm Tanks to Carnwath Road Riverside tunnel section(6.5 m ID) would be 632 m/hr or 0.18 m/sec. This is an exceedingly low velocity that

might account for a pressure loss of 5 to 7.5 kPa over its 6,950 m of length. The Carnwath Road Riverside to Abbey Mills Pumping Station section (7.2 m ID) would have an air velocity of 515 m/hr or 0.14 m/sec. Some of that air would be, under Alternative A, redirected to Abbey Mills and some to the Acton Storm Tanks. Assuming the air in 8,000 m length of tunnel would be directed to the Acton Storm Tanks another 5 to 7 kPa in pressure drop would be realized and the fans would need to provide 10 to 15 kPA of suction pressure. Discharge pressure through the carbon system may add another 15 kPa of pressure drop. Thus, the exhaust fans would need to move 21,000 m3/hr at 25 to 30 kPA. In odour treatment systems, this would not require a particularly large or powerful fan. In fact, a fiberglass fan meeting these specifications would have a wheel diameter of perhaps 1200 mm and consume 20 – 25 kW of power. This type and capacity fan is readily available from numerous suppliers.

It is understood that the system is dynamic and that pressure losses will increase as the tunnel fills, but the air flow rates would decrease to compensate for that effect. The impact on the exhaust fans cannot be estimated without modeling. However, it can be said that doubling the capacity of the fans would again not result in unusual design requirement. CDM Smith has designed several installations with fans larger than 75 kW motors.

Noise is an issue with any fan. Slower rotating and physically larger fans will produce less noise than smaller and faster fans but even then sound attenuation enclosures should be provided in urban environments.

Attenuation enclosures may be purpose built weather-proof enclosures or the fans could be installed in buildings. Either way, the physical dimensions of fans under consideration would not preclude their installation at the Acton Storm Tanks.

As a further note on the design for the preferred scheme, the design indicates that 3 active vents are to be used at the Carnwath Road Riverside site which seems to be an appropriate design. The ventilation stack design however appears inappropriate as in normal design procedures to ensure adequate air velocity leaving the stack, the top of stack should be narrower than base to provide a high enough exit velocity that will disperse the air with a minimum of downwashing . It is proposed that the current design as indicated in available documentation would result in downwash of residual odours on exit of ventilation column.

Section 7 References

1. Thames Water Utilities Ltd., January 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Engineering Design Statement, Doc Ref:7.18.*

2. Thames Water Utilities Ltd., January 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Planning Statement, Doc Ref:7.01.*[1]

3. OJEU, July 2013. *Contract Notice for Thames Tideway Tunnel*. [online] Available at: http://ted.europa.eu/udl?uri=TED:NOTICE:252648-2013:TEXT:EN:HTML&tabId=1 [Accessed: 15 Oct 2013].

4. Thames Water Utilities Ltd., Spring 2010. *Preferred Scheme Report Appendices.*

5. Thames Water Utilities Ltd., 2011. *Phase two scheme development report – Appendix G – Carnwath Road Riverside*. [online] Available at: http://www.thamestidewaytunnel.co.uk/doclib/phase-two-scheme-development-report-appendix-g-carnwath-road-riverside/?came_from=411 [Accessed: 01 Oct 2013].

6. Thames Water Utilities Ltd., September 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Ground Investigation Report on Route Geology (Part 1 and Part 2), Doc Ref: 9.18 .*

7. Thames Water Utilities Ltd., January 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Air Management Plan, Doc Ref: 7.14.*

8. Thamestidewaytunnel.co.uk. 2013. *Contractors shortlisted for main work on Thames Tideway Tunnel*. [online] Available at: http://www.thamestidewaytunnel.co.uk/2013/10/29/contractors-shortlisted-for-main-work-on-thames-tideway-tunnel/ [Accessed: 31 Oct 2013].

9. Thames Water Utilities Ltd., September 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Tunnel and Bridge Assessments - Western Zone - TWUL Thames to Lee Valley Raw Water Main (Tunnel Assessment Report), Doc Ref: 9.15.07.*

10. Thames Water Utilities Ltd., September 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Tunnel and Bridge Assessments - Central Zone - National Grid Wimbledon to Kensal Green Cable Tunnel, Doc Ref: 9.15.36.*

11. Thames Water Utilities Ltd., January 2013. *Thames Tideway Tunnel - Application for Development Consent (Application Reference Number: WW010001), Book of Plans - Works Plans and Sections, Doc Ref: 2.01.*

[1] Including Appendices for each shaft site

Appendix A: Benchmarking Database

	General Information		Shafts				Tunnel Geometry			Tunnel Construction Issues						
Ref No.	Project Name & Country	Year constructed	No.	Dia, m	Depth, m	Support Type	Drive Length, km	ID mm	Depth to Springline, m	TBM	GW, bars	Ground type	Advance-ment Rate	Interventions		Comments
														Ground support	No.	
1	Brightwater East BW-1 WA, USA	2009	4	24.3	24.3	diaphragm	4.3	5870	49	EPB						BW-2 and BW-3 in one contract
				25.6	25.3	diaphragm										
				25.6	25.3	diaphragm										
				20	12	diaphragm										
2	Brightwater Central BW-2, WA USA	2011	1	15.8	27	diaphragm	3.5	5120	30 to 140	STBM		glacial sand, gravels boulders, hard silt and clay				Intervention defined as person/shift did over 1000
	Brightwater Central BW-3, WA USA	2012	1	7.3	62.5	frozen soil	6.1	5120	30 to 100	STBM/EPB	7.3					BW-3 STBM stuck and tunnel completed with GF and continuation of BW-4 EPB machine 3.3km from shaft at depth of 80 m
3	Brightwater BW-4, WA USA	2011	1	5	11	diaphragm	6.4	4000	30 to 100	EPB						
4	Portland, West Side CSO, OR USA	2006	5			diaphragm	6.1	4270		EPB						
5	Portland, East Side CSO OR USA	2009	4	16 to 19.7	36 to 54	diaphragm	6.9	6700		EPB						
5	Portland, East Side CSO OR USA	2010	3				3.5	6700		EPB						
6	Jollyville TX, USA	2013	4		range from 67 to 106		1.4	2900		double shield		soft rock				
							6.7	3250		main beam						No intermedate shafts, tunnel downhill
							2.6	3250		main beam						
										double shield						
7	LA Outfall - CA USA						11.2	5500								
8	Emisor Oriente, Mexico City Mexico		23	16	80-150	slurry walls/shotcrete	10.0	7800	200	EPB		compacted gravel, sand, clay with basalt rock and boulders (0.6 m				six drive segments of about 10 km each. Tunnel bore dia 8.7 m and finished dia of 7.0 m. Steel lined with concrete segmental lining
9	Blue Plains Tunnel Wash DC USA															
10	Port Mann BC Canada	2014					1.0	2800		EPB	6.0			compressed air		
11	Siphon Tunnel NY USA	2014	2	8.5	35	diaphragm	2.9	3000		EPB	4.0		17m/day	compressed air		Flooded tunnel (Sandy) due to surge at shaft
11				7.3	24.3											
12	South Bay Outfall SanDiego CA USA	1999					5.8	3980		EPB	7.0	marine siltstone, cobbles / boulders		1.8 bar max at intervention	10	8 interventions used free air, 2 with compressed air. Screw jams due to boulders
13	Channel Tunnel French Side	1991					15.6	5720		double shield		chalk, marl			0	Mainly open mode due to low permeability Chalk
							20.0	8720		double shield					0	
							18.9	8720		double shield					0	
14	Storebaelt Tunnel, Denmark	1994					3.7	8750		EPB	6.3	Marl, mudstone and abrasive sand		2.7 bar max pressure; typical intervention was done under atmospheric pressure	0	TBM not equipped for saturation diving per spec. 3 bars pressure applied, 16 collapes cost $32 million in delays. Interventions spaced at 124m
15	4th Elbe Tunnel	2000					2.6	14200	10	Slurry	4.2	sand, marl, boulders		4.5 bar max	2738	237 Interventions > 3.6 bars 21 illness cases; face collapse at 4.5 bars
16	Wesertunnel Germany	2002					1.6	11700	17	Slurry	4.0	loose sand, boulders, soft clay	4m/ day	5.0 bar max	1400	Used endoscope inspection remote camera - adv rate improved

	General Information		Shafts				Tunnel Geometry			Tunnel Construction Issues						
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														Ground support	No.	
17	Westerschelde Tunnel, Netherlands	2001					6.6	11330		Slurry		f-m dense sand, stiff clay		6.9 bar max	816	10 interventions used mixed gas; 6 with saturation diving; first time use of divers for cutterhead work
18	St Petersburg Red Line, Russia	2004					0.8	7400		Slurry		glacial - sand and silt		6.0 bar max	NR	long stoppage due to work in high pressure
19	Nara Perfecture Water Conveyance, Japan	1988					1.6	3950		EPB		silty clay gravel cobbles/ dense gravelly sand			0	3 screw conveyors
20	Wan Aqua Line Tokyo Japan	1997					4.6	14140		Slurry		soft marine silty clay over weakly			0	tunnels with 4 headings with GF
							4.5	14140		Slurry						
21	Madrid Highway M30,	2006					3.6	15200		EPB						
22	Chongming, China	?					7.2	15600		Mixshield						twin tunnels - planning stage
23	SMART, N S-252 Malaysia						5.4	13210		Mixshield		limestone, sand marble				
23	SMART, S S-253 Malaysia						4.0	13210		Mixshield		limestone, sand marble				
24	S-221Metro Barcelona Line 9, Spain						8.5	12060		EPB		Grandinorite, sand, clay & gravel				
25	Big Walnut Augmentation /sewer	2004					6.1	4267		EPB		gravel, sand Boulders				TMB type selected based on high quantity of boulders expected. Conclusion: do NOT use disc cutters to cut boulders with EPB
26	East Side Access Queens NYC USA	2013				ground freeze	1.2	6700		Slurry		rock mixed face soft grd with boulders				safe havens for repairs; cutter head - hard facing; cutter mono-block (boulder protection)
27	Izmir Metro Stage 1 - Turkey	?					1.4	6560		EPB		Gravel, sand, sitly sand	15m/day			Settlement prediction vs measured - building clearance issue
28	Port of Miami - FL, USA	2014				diaphragm	1.4	12500		mix shield	3	loose sand, soft calcarioius sandstone				two tunnels one TBM rotated on table to do both tunnels without removing from ground. Ground freeze use for 2 cross-passages
29	Alaskan Way Viaduct, AK, USA	2013					3.2	17500				sand, gravel, clay				
30	Southern Tunnel Ext. (Brixton to Honor Oak), London, UK	2010		11	55-60	dry caisson jacking	4.9	2500				mottled clays, sands and chalk				
31	Greater Cairo Waste Water, Cairo, Egypt	1992	22			pneumatic caissons	12.2	6100		Slurry		silts and clays, underlain by sand				
32	Lesotho Highlands Water, Lesotho/South Africa	1996					16.0	4500				soft rock and marl				Very high pressures made marl unstable. Total length 28 km
33	Melen Water Supply, Istanbul, Turkey	2011		8	145		3.4	6100					7.4 m/day			Underwater by 70 m and separated from Bosphorus Sea by about 35 m of overburden
34	Bristol Bulk Handling Terminal	1993					0.4	3400		EPB	3	alluvial silts, clays, sands and gravels with hard conglomerate at deepest pt.				Crossing below River Avon with only 6 m of cover

	General Information		Shafts				Tunnel Geometry			Tunnel Construction Issues						
Ref No.	Project Name & Country	Year constructed	No.	Dia, m	Depth, m	Support Type	Drive Length, km	ID mm	Depth to Springline, m	TBM	GW, bars	Ground type	Advance-ment Rate	Interventions		Comments
														Ground support	No.	
35	Delhi Metro, India					diaphragm, secant pile, king pile	4.1			EPB		soft ground				twin bored tunnels with sensitive structures overhead
36	Porto Metro, Portugal, Spain	2003					7.0	9000		EPB		granite to decomposed/loose rock				
37	Heathrow Airside Road, London, UK	2004					1.2	9160	15-20	EPB		London clay underlain by Thames gravel	TBM penetration rate 50 mm/min			Shallow twin bores under and over sensitive utilities 3 m clearance
38	Sydney Airport Rail Link, Sydney, Austrailia	2000				slurry wall and diaphragm with dewatering system	6.0	10750		EPB & Slurry		Soft alluvial deposits and marine deposits				Bored under terminals and runways; decompression illness rate of 0.35%
39	Northern Diversion Sewerage, Melbourne, Austrailia		8	13	65	secant piles	8.0	1600-2500		EPB		Siltstone with basalt intrusions and alluvial soils (Brighton Group)				
40	Eyholz Tunnel, Switzerland	2012					4.3	12600				soft ground				Twin bores
41	Beijing Metro Line 9, China	2012					2.4	6250		EPB		granular soil with boulders (~1.2-1.5 m dia.; spaced at ~4 per L.M. of tunnel)				Passed under 1 river and 2 lakes; under water table at all times; cutting head rippers (Tungsten Carbide inserts) worked well on boulders
42	16th Ave Collector, Ontario, Canada						3.7	3300		EPB		tills, silty clays and sands with cobbles and boulders				Entire tunnel below water table
43	Colector Central Fontibon & Centenario, Bogota,	2007				steel sheet piles	1.0	2800		Slurry		fine sand and soft clays				
44	Bankside to Farrington Cable Tunnel, London, UK		5				1.1	2590				soft ground				
45	Caracas Metro Line, Venezuela						4.8	5880		EPB		sandy silt and silty sands with				
46	Metro Seville, Spain		6		15	triple-lined concrete stations	3.6	5300	15	EPB	2.2	rounded, coarse gravel with sand and blue marl				High wear-rate due to abrasive gravel and triple-lined concrete stations; certified divers required to repair cutting face
47	Hydroelectric Plant, Machu Picchu, Peru						0.2	3100	43-48	Slurry		silt, clay and silty sand				Twin bores

Appendix B: Benchmarking Sources Searched

B.1 Benchmarking Approach Used

The first step in establishing a benchmark is to identify similar projects and build a database of those projects with relevant parameters. In the process of collecting this data a significant number of projects that were reviewed were not used (or filtered out) because of major significant technical differences. One key filter we used to develop the database for use in this assessment was that we only considered tunnels that were excavated in soft ground or soft rock using slurry, EPB or double shield TBM. The ability to quantify engineering parameters so that contractors can adequately address the issue of wear to the TBM cutters is much more advanced in ground that is rock, than ground that is soil. Therefore only selecting soft ground tunnels with EPB or double shield TBMs was considered key to benchmarking because of the difficulties and safety risks associated in soft ground tunnelling that are less of a risk issue with rock tunnelling. All five parameters identified in Section 3 are encountered in soft ground tunnelling. The probability of each risk affecting project cost and schedule is related to the drive length.

One obstacle of Alternative A raised by Thames Water was the increased concern of the TBM getting stuck under the river or residential areas with no means of accessing it for repairs. The data to developing a database to benchmark this concern is limited. We addressed this concern by benchmarking soft ground tunnels and the drive length. In effect that effort as shown from the summary of the data base in Appendix _ tunnels of 12 km can be driven.

When abrasive soil causes problems outside of the machine shell, accessing the problem areas can be very difficult and costly.

There are very few published articles that detail abrasive wear on the cutters and the related interventions required to inspect and maintain cutters. This made collecting sufficient data to use as a benchmarking database for this parameter impractical.

In today's tunnelling the condition of the cutters on the TBM face is constantly monitored and a more detailed evaluation by inspections and maintenance is performed as required during the drive. Frequency of these interventions can be given as specification requirements.

Maintaining tunnel grade and alignment is critical for tunnels. The consequences of a misalignment are related to the magnitude of the misalignment and the problems that occur because of the misalignment. Consequences can include: change in tunnel slope, tunnel out of easement or right-of- way, too close to or interfering with existing infrastructure; or, leaving insufficient room for future infrastructure.

The technology exists today to perform this survey and to monitor in real-time 3-D location of the tunnel heading. In addition to location, the loads acting on the tunnel, pressures induced by the tunnel on the ground, ground behaviour and cutting tool behaviour can all be monitored at any time. Such information aptly interpreted can eliminate problems with line and grade. These same survey capabilities are also possible for tunnel alignments with compound and reverse curves. Very seldom is a tunnel on a straight line today with no curves. Published articles provide limited information on details of alignment geometry. Therefore we did not benchmark this parameter based on published data. We reviewed some in-house data regarding survey and maintaining line and grade. We have observed that throughout the industry it is common to see more drift to line than grade tolerance.

Tunnelling beneath open water presents a challenge with regards to pressure applied to the tunnel face to maintain stability. The driving force into the tunnel face is the soil and the hydrostatic pressure. The resisting force is the applied pressure which is limited to the strength of the saturated soil. Excess face pressure can cause the soil to fail and allow water to enter the face. For this project the majority of the tunnelling is done under open water and therefore we consider this risk the same for the preferred scheme and the two alternatives being considered. The benchmarked projects did not differentiate projects as tunnelling under open water or land.

B.2 Benchmarking Sources Searched

The sources that we used in assembling our benchmarking database consisted of in-house sources, interviews with TBM manufacturers and published papers on soft ground tunnels of similar size and length. Data from the publications is summarized in Appendix A of this report.

We also evaluated in-house projects that had similar elements such as length of tunnel drive, tunnelling under high hydrostatic pressure, interventions spacing. Two in-house projects that had similar characteristics to the TTT were selected to demonstrate actual risks that were mitigated, or encountered and resolved (see Section 4.2.1): the Brightwaters Conveyance Tunnels, Washington, USA and Jollyville WTP-4 Tunnels Austin Texas, USA.

We also had telephone interviews with TBM manufacturers. These interviews focused on recent advances in technology including, probing and grouting capability from within the TBM, cutter disc wear and hyperbaric chambers for interventions performed under compressed air.

The lessoned learned from the in-house projects are presented in Section C.1.1 whilst the results of the telephone interviews with TBM manufacturers is presented in Section C.1.2.

B.1. 1 In-House Projects

The first project we have a significant amount of detailed information on is Brightwaters Conveyance Tunnels for which we provided geotechnical services throughout the design and construction. This project consisted of three tunnelling contracts and four long soft ground tunnel drives. The second project is the WTP-4 Tunnels.

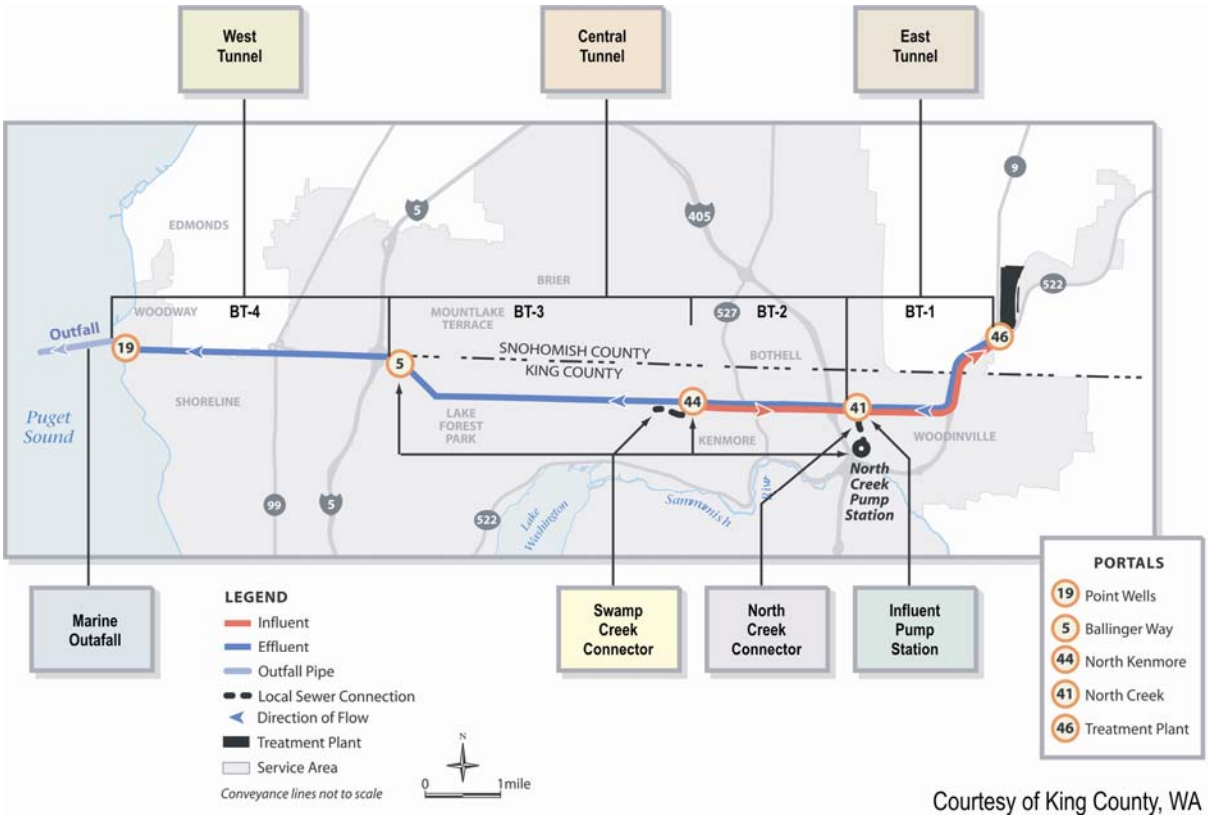
The second project is Jollyville WTP 4 Tunnels in Austin; in our role as a consultant to the City of Austin we have limited overall project information but sufficient information on survey control to produce some important lessons learned on that major issue for this project. This project consisted of three tunnel drives in soft rock.

The following is a brief summary of these two projects and the lessons learned from them:

Brightwater Conveyance, Kings County, Washington USA

The Brightwater tunnels include about 20.4km of large diameter (range of 4,000 mm IDto 5,870mmID) tunnels excavated in four segments. The original project schedule was developed based on the system including a new Waste Water Treatment Plant being operational by 2010. Design started in 2002. Looking for consistency in addressing geotechnical issues one firm was selected to perform all of the conveyance geotechnical work.

Figure 6: Scheme Layout, Brightwater Conveyance Tunnels, Kings County, Washington USA



The ground conditions for all three contracts was similar consisting of three different glacial advances and retreats resulting in north south trending ridges and valleys perpendicular to the east –west tunnel alignments.

Over 200 explorations were drilled with an average depth of 81m. GBR's were prepared for each contract. The owner felt comfortable with setting expectations on ground conditions and accepting a reasonable amount of risk. Also some risk was taken in the specification to reduce risk. These mitigation efforts included: requirement of a certain level of equipment spares; TBM inspections; and, TBM operational requirements. The GBR's indentified soil types based on tunnelling behaviour and ranges of tunnel lengths that could be expected for each soil group. Groundwater head was established. Boulders were known to exist, and quantities, boulder strength and ability to stay within the soil matrix when encountered were quantified in the GBR. The stickiness of the clays was also baselined for each contract.

The length of these tunnels required good planning and execution of the tunnelling systems. The specifications required the contractors to make a minimum number of inspection stops based on the geotechnical conditions and TBM operations. A separate pay item was used for this activity.

The East Tunnel contract consisted of one tunnel drive (BT-1) of 4.2 km of 5,870mm ID precast segmental lining. A total of three shafts were designed: an influent structure 22.5 m deep by 24.3 m diameter within a slurry diaphragm excavation and a twin intersection 25.6 m diameter cells for a pump station 25.3 m deep also with slurry diaphragm walls and receiving shaft that was modified by the contractor to a rectangular exit pit for easier removal of the TBM. Tunnel was excavated using an EPB TBM and completed on schedule.

A major change in the design raised the elevation of this tunnel by approximately 100 feet from the stiff to hard clays to the overlying sand and gravel. This option significantly reduced the hydrostatic pressure on the tunnel face reducing the risk associated with intervention work under high compressed air requirements for stability. The trade off was some additional cost in soil conditioning additives to the face.

The Central Tunnel contract consisted of two tunnel drives. Slurry TBMs were specified for both drives (BT-2 and BT-3). Both drives used 5,120 mm ID slurry TBM's. BT-2 was 3.5 km in length and BT-3 was 6.1 km. A launch shaft for the BT-3 was 15.8 m diameter by 27 m deep supported by a slurry diaphragm wall. The receiving shaft was 7.3 m diameter shaft 62.5 m deep that was supported with a full length frozen soil wall and bottom seal.

The BT-2 tunnel passed within a few meters of an aquifer without significant incident. The B-3 tunnel encountered significant cutter wear and was stopped about 3km short of the receiving shaft at a depth of about 78 m and under 4 bars of pressure. This machine was abandoned in place and the tunnel completed by extending the tunnelling of the west bound BT-4 from the West Tunnel Contract and tunnel into the stripped shell of the BT-3 machine. Ground stability for this operation consisted of ground freezing from both the surface and from the face of BT-3 to form a frozen mass around the entire BT-3 machine. This operation was successful and the tunnel completed about 1.5 years behind schedule.

The excessive machine cutter wear appeared to be a combination of the very abrasive soils and applied pressure on the face to advance the machine. The slightly smaller BT-4 EPB TBM did not have any problems advancing through the same geology and pressure heads up to 7.3 bars to meet up with the stuck machine.

The West Tunnel Contract consisted of 6.4 km of tunnel with a minimum diameter of 4,000 mm. Approximately 0.8 km of this tunnel included a secondary lining of steel that was 3,000 mm in diameter. The launch shaft was a water tight structure 11m deep. This tunnel was originally scheduled to exit into the same exit shaft used for the BT-3 drive. However, as detailed above, this interface was ultimately not used as planned due to the problems encountered on the BT-3 drive which resulted in the BT-4 machine being driven from the location of the abandoned BT-3 TBM shell.

The number of interventions that were performed for all of four of the Brightwater tunnel drives is summarized in Table 4-1. As can be seen in this table the number of interventions was not only a function of tunnel length but also of the ground conditions which varied significantly, the type of TBM used, the operator of the TBM and the amount of risk each contractor was willing to take. We distinguished between inspection stoppages and interventions requiring crew at the face either in free air or working in compressed air conditions.

Table 10: Summary of Brightwater Interventions

Tunnel	Length, km	TBM Type	No. of Inspection stoppages / Interventions	Max Press bars	Remarks
BT-1	4.6	EPBM	9 / 0	> 3	Less inspection stops were performed than specified.
BT-2	3.3	STBM	33 / > 395	5.8	Cutterhead repair required large number of interventions.
BT-3 excluding 3C	3.8	STBM	34 / > 175	5.6	The BT-3 TBM was abandoned. Tunnel was completed by another TBM (see BT-3C)
BT-3C	3.2	EPBM	15 /14	0	Cutterhead equipped with flood doors that could be hydraulically closed; intervention strategy was to always attempt atmospheric interventions in a stable clayeytunnel face
BT-4	6.9	EPBM	39 /12 successful man-entry interventions, 27 attempted camera inspections that were largely unsuccessful	3.3	Cutterhead equipped with flood doors that could be hydraulically closed; intervention strategy was to always attempt atmospheric interventions in a stable clayey tunnel face

The duration of a hyperbaric intervention with man-entry was based on the length of the work shift, i.e. typically around 8 hours, unless the work was be completed in less time. Work achieved in one intervention depended on the hyperbaric pressure. That pressure established necessary lock-in and lock-out times. The number of interventions performed at an inspection stop function of work required. There was significant amount of cutterhead repair work that was required at BT-2 and BT-3, resulting in large numbers of interventions. These were Slurry TBMs.

There are valuable lessons learned from these Brightwater tunnels especially with regards to the limited amount of what we know about soil abrasion and its effect to the exposed steel of a TBM. We know that there are many factors that affect the TBM performance and not just limited to ground conditions. As a result the risk associated with soil abrasion to a tunnelling project remain subjective. It is not possible to benchmark this parameter except in general terms regarding the abrasiveness of the soil. Based on what we do know is clay soils tend to be less abrasive than coarse silts and fine to medium sands with high quartz and feldspar mineral contents. In that perspective the affects of a longer tunnel drive required of either Alternative A or B compared to the preferred scheme would not be expected to significantly increase risks of a TBM wearing out due to abrasion.

Jollyville WTP-4 Tunnels Austin Texas, USA

This project included construction of four shafts, two drive and working sites and two TBM reception shafts . Shafts ranged in depth from 67m to 106m. No other shafts were allowed for this work because of the environmentally sensitive land that the tunnel was passing under. Three tunnel reaches of 1.4km, 6.7km and 2.6 km were excavated in the Glen Rose rock formation, a dolomite and limestone with an average UCS value of 13.7 MPa. The tunnels were driven using one double shield TBM for the 1.4 km reach, 3,250mm bored diameter main beam rock TBM and a refurbished 2,900 mm double shield. All of the tunnelling was performed down gradient.

Because of the very good to excellent rock quality little initial support was required. The specifications limited the amount of inflow into the tunnel that would be allowed before ground modification would be required to reduce the flow. This requirement was established to mitigate the risk of lowering the groundwater in the semi-arid country.

The most significant issue that has occurred in this construction is the deviation from line and grade. The tolerance on line was 150mm and deviations of as much as 2300 mm have occurred. Deviation from grade was less than 100mm. Cause of the TBM deviating from alignment was determined to be a thrust cylinder in the TBM not operating properly. The problem was not observed because there was no continuous monitoring of TBM behaviour and survey was performed by the crew and data reported to the tunnel engineer several days after the survey was completed.

As a result of the misalignment there is now concern with the ability to install a second tunnel parallel with this one and stay within the existing easement and not cause damage to the now existing tunnel.

Since the vast majority of tunnels are completed within specified tolerance for line and grade few published papers report a success therefore developing a reliable database of this surveying risk parameter is questionable. This project demonstrates that constant vigilance to TBM operation and interpretation of the available data of machine performance can further mitigate the risk of not maintaining alignment independent of the tunnel length.

B.1. 2 TBM Manufacturers

We talked to representatives from both Herrenknecht and Robinson regarding the recent advances in TBM design. Specifically to address the issues of providing access in the TBM shield to perform probing in advance

of the TBM, modifications to disc cutters to improve cutter life when encountering boulders and provisions for hyperbaric chambers in the tunnel to reduce risk to miner safety.

Cutter Tool Changes

Depending on the ground conditions both EPB and slurry machines types can be equipped with cutting tools that include scrapers to bring loosened material into the cutter head openings, rippers (drag bits) to excavate soil, and disc cutters to cut any rock that may be encountered. Each cutter type can be installed using mounts that can be back-loaded to aid in changing cutters during long tunnel drives. To change the cutters during tunnelling the TBM face must be stabilized usually by being pressurized to maintain face stability and workers enter the compressed air environment using an airlock. The two manufactures that we talked to stated that there have been some effort on very large TBMs, with diameters greater than 10 meters, to develop methods to allow cutters to be changed with the use of compressed air that is limited to a small area sufficient to allow for the miner to access the cutter from the back. The advantage to this would be that the face stability using compressed air would be limited to a small portion of the tunnel face rather than having to stabilize the entire face. For large diameter machines just the variation in pressure due to the height of the machine causes problems in balancing pressures. This method is still in the experimental stage and no feedback on its success is presently available. At this time all the methods are in the development stages and some form of air lock is still required.

A lesson learned from these conversations was the technology advancement comes from a specific need. In this case the diameter of the machine (15m) makes applying a uniform pressure to maintain face stability risky because of the change in the pressure acting on the face from top to bottom. What works for one machine in one set of conditions may not be available for other applications. A similar lesson is discussed in Appendix D of this report with regards to types of TBM's and the limitations on new advances in the technology.

Ground Conditioners

Soil conditioners used for EPB tunnelling provide the added benefit of reducing abrasion wear and extend cutting tool longevity. This is important for tunnels which have a long TBM drive with no access to the machine through intermediate shafts. At this time the manufacturers stated the beneficial gains from ground conditioners have not been studied to any great degree. Some contractors have developed methods they believe extend the life of their equipment but they are unwilling to share the information and consider it proprietary knowledge. At this time the only reliable way to extend the life the cutters in a soft ground tunnel is to construct more robust cutters therefore increasing the time it will take for the soil to wear away the steel.

Probing and Grouting

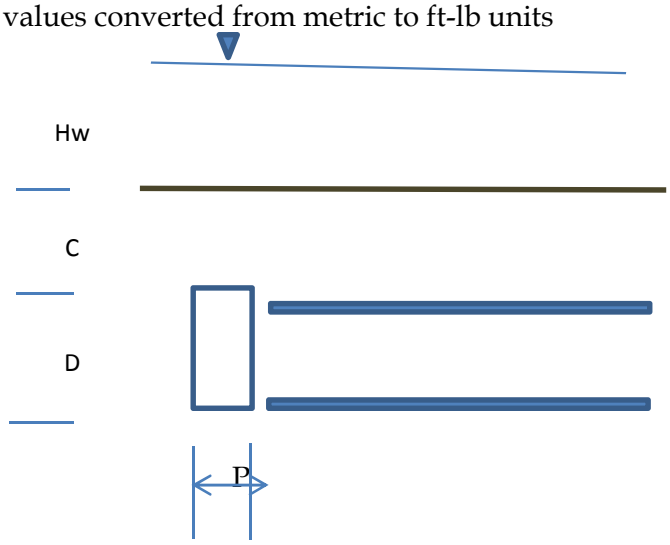
Encountering unknown ground conditions during construction pose one of the greatest risks to the successful completion of tunnel projects. Poor ground conditions can result in safety concerns, difficulty in mining, inability to maintain line and grade, create surface settlement delay schedule and increase costs. Probing is typically performed by drilling a series of drill holes around the periphery of the TBM cutterhead. Each hole is typically drilled at an angle of 4-7 degrees from the tunnel alignment. If unsuitable ground conditions are encountered grouting or other methods can then be used to stabilize the ground. Based on our discussion with the TBM manufacturers there has been little change in this methodology for several years. Some attempts at using geophysical instruments to map the ground ahead of the TBM have been tried but have proved to be inconsistent at best.

The ability to probe ahead exists and contractors have a good understanding of the limitations this technique presents. Knowing what is on the market also helps them to establish the level of risk they are willing to take.

Appendix C: Calculations

Thames Tidewater Tunnel - Hydrostatic Pressure and Maintaining Face Stability

All input values converted from metric to ft-lb units



Tc = Tunnel Stability Number as function of C/D and P/D

Input Data

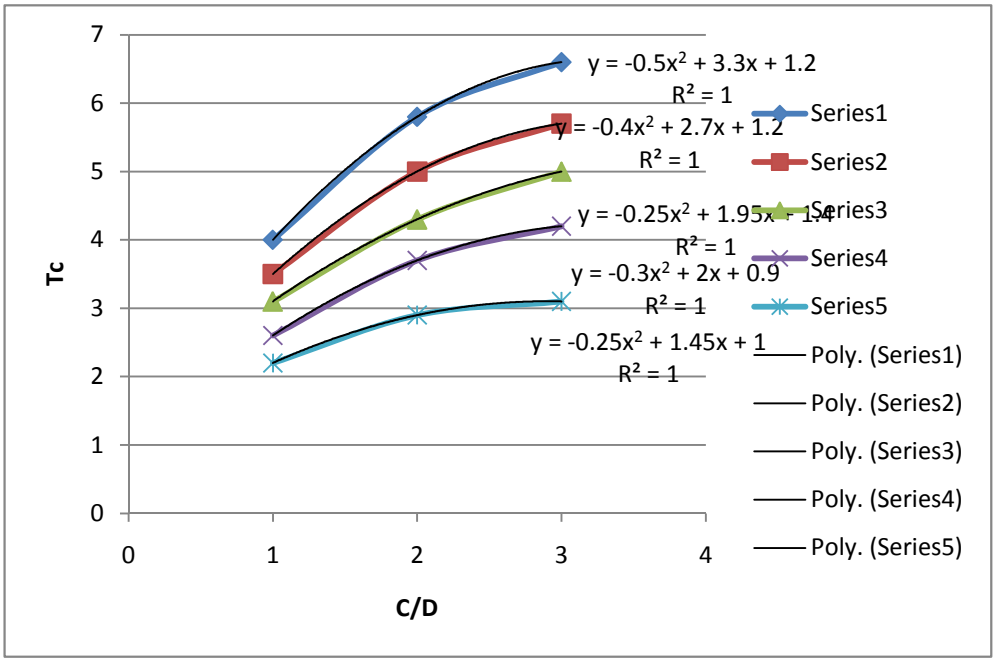
Total overburden cover, ft, C =	61	under water measure from mudline
Tunnel diameter, ft, D =	21.96	
Unlined length, ft P =	3	
Average total weight, δ_t =	128	
Shear strength, psf, Su =	10000	
Hw ft =	15.25	Water depth above mudline
Surcharge pressure, psf σ_s =	960.75	
Internal Tunnel pressure,bars, σ_T =	2	
Internal Tunnel pressure, psi, σ_T =	29.0	
Internal Tunnel pressure, psf, σ_T =	4177	

Calculated values

P/D =	0.1	
C/D =	2.8	
Tc =	3.1	Tunnel Stability number from Atkinson andMair, 1981
Fs =	**5.2**	Factor of Safety of tunnel face stability

If C/D ratio exceeds 5.0 you can consider reducing the C value to account for soil arching

	P/D				
C/D	0	0.5	1	2	∞
1	4	3.5	3.1	2.6	2.2
2	5.8	5	4.3	3.7	2.9
3	6.6	5.7	5	4.2	3.1



	Tc as function of C/D and P/D				
Tc	6.5	5.6	4.9	4.1	3.1

Confirms that the face pressures are within a manageable range and in clay may be able to do an intervention without need for compressed air

Tunnel Alignment curvatures going up station from Abbey Mills

	Curve #	Length, m	Radius,m			Footage	% Curved
Shaft #23	Abbey Mills			Chainage	22450	5520	26%
	1	107.6	600				
	2	219.8	600				
	3	129.7	600				
	4	435.6	600				
	5	282	600				
	6	269	600				
Shaft #17	Chambers Wharf			Chainage	16930	7670	21%
	7	55.8	600				
	8	325.7	600				
	9	280.3	600				
	10	110.2	600				
	11	120.3	600				
	12	146.7	600				
	13	152.4	600				
	14	219.5	600				
	15	119.6	600				
	16	106.2	600				
Shaft #15	Kirtling Street			Chainage	9260	5060	71%
	17	182	600				
	18	558.7	600				
	19	191.5	600				
	20	257.1	600				
	21	351.5	600				
	22	284.2	600				
	23	140.3	600				
	25	774.9	600				
	26	244.3	600				
	27	370.8	600				
	28	226.4	600				
					Carnwath Road to Hammersmith		
#7 Carnwath Road Riverside				Chainage	4200	4200	35%
	29	221	600				
	30	311.2	600				
	31	202.5	600		Carnwath Road to Barn Elms		
Shaft #3	Barn Elms			Chainage	1770	2430	30%
	32	248.5	600				
	33	329.9	600				
	34	152.5	600		Barn Elms to Hammersmith		
Shaft #2 Hammersmith PS				Chainage	0	1770	17%
	35	882.7	500		Hammersmith to Acton		
	36	105.4	400	Chainage	2700	2700	60%
	37	125.6	400				
	38	193.1	400				
	39	82	400				
	40	91.7	400				
	41	70.3	400				
	42	59.2	400		Carnwath Road to Acton		
Acton Storm Tanks				Chainage	6900		45%
					percent of total alignment on curves		39%
					percent of open water tunnel alignment on curves		36%
					percent of land alignment on curves		60%

Appendix D: Discussion on Hybrid TBM (EPB/Slurry)

D.1 Risk Associated with TBM Selection

As described in the existing planning documents the present consideration is that three of the four main tunnel drives: Carnwath Road Riverside site to Acton Storm Tanks; Kirtling Street to Carnwath Road Riverside;Kirtling Street to Chamber Wharf will use an EPB /TBM. The fourth drive from Chambers Wharf to Abbey Mills Pumping Station will be excavated using a Slurry TBM. All of these tunnels are 7,200mm or less in diameter. This is a key parameter with regards to both consideration of overall risk of drive length and must be taken into account with regards to a decision when consideration of utilizing a hybrid machine is made.

There are relatively consistent parameter guidelines for optimal efficiency of TBM type for given ground conditions. There are also mitigating conditions that may result in a different machine type being selected by a contractor. Such conditions would have to be evaluated on a case by case basis. Such a decision should be the contractor's based on the level of detail presented in the tender documents. At this time this decision on selection of machine type is considered to be a contractor's risk. The technical basis or ground conditions for selection is the geotechnical data presented in those same documents. The sufficiency and accuracy of this data is the owners risk.

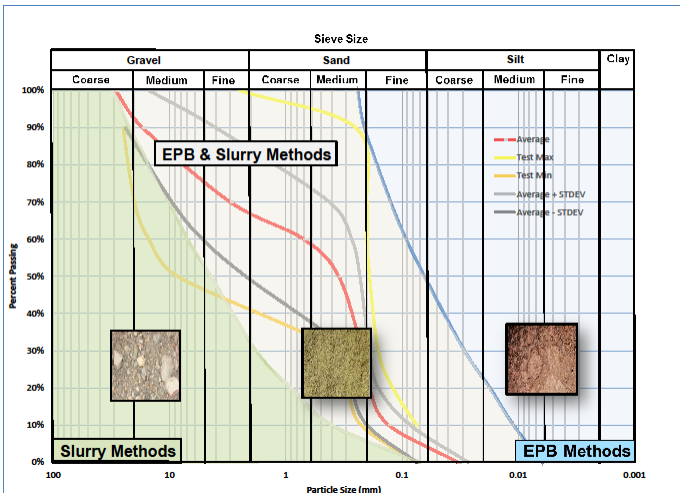


Figure 2-7 - Soil Gradations and Optimal TBM Type

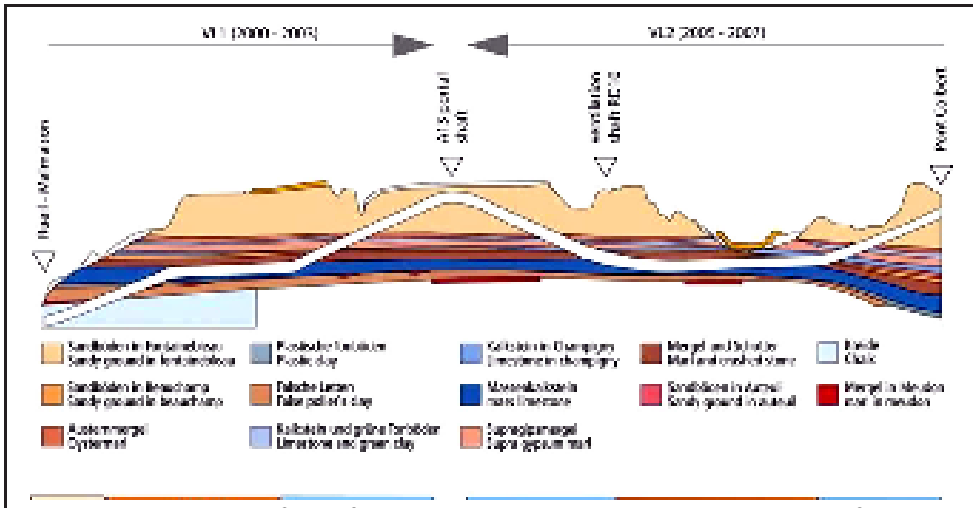


Figure 2-Error! No text of specified style in document.**-8 - Socatop Tunnel Profile**

As a function of ground conditions soft ground tunneling is performed using either open-face or closed-face TBMs. The open face machine relies on the ground strength and anticipated behavior under tunneling conditions when advancing the tunnel. This machine is used for non-water bearing ground and under atmospheric conditions. A closed-face machine provides support which in effect seals the tunnel from the ground and hydrostatic pressures. There are two types of closed-face TBMs: Earth Pressure Balance and Slurry or mixed shield.

The EPB machine provides face support by using the soil being excavated to partially fill the excavation chamber, located behind a plenum. This type of machine works best in cohesive soils where the soil can forma plug in the screw used to remove soil from the excavation chamber. Coarser grained soil will have a tendency to flow under the hydrostatic pressures and measures in the form of soil conditioners have to be

added to control this behavior. This action results in loss of efficiency and increased cost due to the conditioners and loss efficiency. Advances in admixtures have helped to improve the efficiency of the EPB machine in a wider range of soil types.

Slurry machines inject a bentonite slurry into the face of the soil being excavated to reduce the soils permeability. With the reduced permeability an applied air pressure provides the face stability. The slurry injected into the soil is recycled at a slurry separation plant. This machine works more efficiently in cohesionless soils because of the ability to separate the slurry from sandy soils in comparison to clayey soils.

One consideration with large diameter machines is that the pressure applied to the face is uniform with an EPB machine whereas the pressure applied to the saturated soil from a slurry machine more closely matches the differing pressure across the vertical face of the machine. In certain conditions this ability to control face pressures especially when under open water and shallow cover may favor the use of a slurry machine in finer grained soils.

The hybrid machine that has the ability to convert from slurry to EPB is new to the tunneling market. While machines have switched from open face mode to either slurry or EPB closed face mode have been done quite often to date we are only aware of one project - Socatop in Paris, France that utilized the switch from slurry to EPB while on the same drive. As shown in the profile conditions have to be ideal to help justify this cost. Here a 10 km drive consisted of 60% ideal conditions for slurry and 40% for EPB.[2]

There are a couple more of these machines currently being built by Herrenknecht. There are advantages to the ability of this machine to switch modes of face support if the ground conditions and tunnel length allow for the economics.

Criterion used for selection of a type of machine usually focuses on the anticipated soil gradation that can be expected along the entire tunnel drive. As shown in Figure 2- 1 there is a distinct difference in the type of soil that is most efficient for slurry operation mode versus earth pressure balance mode.

The major advantages are:

- Greater efficiency can be attained by taking advantage of discrete ground conditions
- Optimal efficiency will result in optimal cost savings
- Optimal working mode will increase worker safety

There are limitations that have to be considered in making the decision on the machine type. Typical of the information needed to make such a decision are presented in the following text. :

Are the ground conditions sufficient different that there is an obvious requirement for a particular machine to be used in different reaches of the same drive? It takes about 3 days to make the switch over from EPB to slurry or vice versa. This is lost time with regards to advancing the heading. The question: “Are these reaches of sufficient length to make up the lost time?” need to be answered.

Is the tunnel diameter size sufficient to make the change over? Working room for the different muck removal systems in parallel and if a rock crushing is required for the slurry system can become a major issue. To make this switch requires the tunnel diameter of at least 8,000 mm diameter. If providing this working space requires an upsize to the tunnel several items have to be considered in the cost besides just a larger ring segment. Other cost items that could be affected are: shaft size adequate for the larger tunnel diameter, potential for damage to existing infrastructure due to the reduced clearance between tunnel and infrastructure, more spoil disposal.

[2] Multi-Mode TBMs – State of the Art and Recent Developments, Werner Burger, Herrenknecht AG

From a risk delegation perspective the entity in the best position to manage this risk is the contractor and the responsibility to make the TBM selection should be given to the contractor. Mitigation of the risk to the Owner is achieved by providing the most accurate and clearly defined statement of the ground conditions to allow each bidder to make an informed decision.

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