Appendix B – Tunnels

APPENDIX B TUNNELS

B1 INTRODUCTION

The purpose of this appendix is to provide technical background and additional information to assist Transport Scotland in determining the most suitable solution from the different crossing options available at the present time.

This appendix looks at the three preferred tunnel corridors currently being considered for this project, and how each of these alignments is proposed to connect into the existing road network.

A number of other reports have been prepared as part of this study, in particular Report 3: Option Generation and Sifting, published in December 2006. This report looked at an additional two crossing corridors (a total of five), and considered both a tunnel and bridge option for each of the crossing locations. From the findings in this report three tunnel and two bridge options have emerged as favourites. Each of these tunnel options has been earmarked for further development at this stage. The development of the two preferred bridge options has been covered in a separate technical annex.

There are a number of key engineering issues that would help to determine the suitability of each of these three options. These key issues include the following:

- Vertical and horizontal alignments;
- Constructability;
- Ventilation and safety requirements; and
- Costs.

Building on the findings of the earlier studies outlined above, this document seeks to expand on the above matters, and further develop the design of the tunnels in order to help inform the assessment of all of the options.

B2 SAFETY FEATURES AND EQUIPMENT INFLUENCING CROSS SECTION

B2.1 Spatial Requirements

Hierarchy of Tunnel Design Standards

UK road tunnels over 150 metres length are designed to Volume 2, Section 2, Part 9 of the Design Manual for Roads and Bridges (DMRB), BD 78/79 - Design of Road Tunnels, and its associated standards and industry practices. It is assumed that the route would form part of the Trans-European road network. Its design would therefore be compliant with the European Parliament and Council Directive Number 2004/54/EC and its implementation document, The Road Tunnel Safety Regulations 2007 Consultation Draft. These are under consultation at the time of writing, and may be refined further before being implemented. For the purposes of this report, it has been assumed that any Forth tunnel would have to be designed under the criteria set out in the current consultation draft.

Table B1 shows the clauses of the European Union (EU) Road Tunnel Safety Regulations 2007 Consultation Draft that affect the spatial requirements of the tunnel. The table also details their implications on the shape and cross section of the proposed tunnel.

Table B2 shows the clauses of the BD 78/99 that affect the spatial requirements of the tunnel. The table also details their implications on the shape and cross section of the proposed tunnel. The design must comply with the mandatory requirements of the standard which are in bold print or a suitable Departure from Standard must be agreed with the relevant Overseeing Organisation. Where the word “shall” is used, the requirement is expected to be carried out in full, unless, due to constraints of a particular scheme, a recorded agreement has been made with the Overseeing Organisation that another way of satisfying the intention of the requirement is to be used. The remainder contains advice to designers for their consideration.

Table B1 – Spatial Requirements from EU Road Tunnel Safety Regulations 2007

Issue	Requirement	Implication for Forth Crossing
Tunnel Configuration	2.1.2 In any case, where, for road tunnels at the design stage, a 15 year forecast shows that the traffic volume will exceed 10 000 vehicles per day per lane, a twin-tube road tunnel with unidirectional traffic shall be in place at the time when this value will be exceeded.	♦ Traffic volumes for a Forth crossing tunnel are assumed to exceed this threshold so a uni-directional twin tube tunnel is proposed.
Slip Roads	2.1.3. With the exception of the emergency lane, the same number of lanes shall be maintained inside and outside the road tunnel. Any change in the number of lanes shall occur at a sufficient distance in front of the road tunnel portal; this distance shall be at least the distance covered in 10 seconds by a vehicle travelling at the speed limit. When geographic circumstances prevent this, additional and/or reinforced measures shall be taken to enhance safety.	♦ No lane changes or forced merging close to tunnel portals. ♦ Any toll plaza (if required) or junction split must be sufficiently far from tunnel portals, at design speed of 50 miles per hour, this equate to a minimum of 250 metres.
Gradient	2.2.1. Special consideration shall be given to safety when designing the cross-sectional geometry and the horizontal and vertical alignment of a road tunnel and its access roads, as these parameters have a significant influence on the probability and severity of accidents. 2.2.2. Longitudinal gradients above 5% shall not be permitted in new road tunnels, unless no other solution is geographically possible. 2.2.3. In road tunnels with gradients higher than 3% additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis. 2.2.4. Where the width of the slow lane is less than 3.5 metres and heavy goods vehicles are allowed, additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis.	♦ Options generated at 3 % gradient or less where possible. ♦ No options generated with gradients above 5 %.
Emergency Lanes	2.2.4. Where the width of the slow lane is less than 3.5 metres and heavy goods vehicles are allowed, additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis. 2.3.1. In new road tunnels without an emergency lane, emergency walkways, elevated or not, shall be provided for use by tunnel users in the event of a breakdown or an accident. This provision does not apply if the construction characteristics of the road tunnel do not allow it or allow it only at disproportional costs and the road tunnel is unidirectional and is equipped with a permanent surveillance and lane closure system.	♦ Lane width of 3.65m. ♦ Emergency walkways to be provided on both sides of the carriageway.
Lay-bys	2.5.1. For new bi-directional road tunnels longer than 1 500 m with a traffic volume higher than 2 000 vehicles per lane, lay-bys shall be provided at distances which do not exceed 1 000 metres, if emergency lanes are not provided.	♦ Uni-directional tunnel proposed. ♦ In a TBM tunnel, construction of lay-bys would be prohibitively expensive so the total width of tunnel (including verges) would satisfy the requirements of this

	2.5.3. If the construction characteristics of the road tunnel do not allow it or allow it only at disproportionate cost, lay-bys do not have to be provided if the total tunnel width which is accessible to vehicles, excluding elevated parts and normal traffic lanes, is at least equal to the width of one normal traffic lane.	clause.
Safety Niches (Emergency Points)	2.10.3. Emergency stations shall be provided near the portals and inside at intervals which for new road tunnels shall not exceed 150 metres and which in exiting tunnels shall not exceed 250 metres.	♦ Safety niches at maximum intervals of 150 metres.
Fire Resistance	2.7. Fire resistance of structures The main structure of all road tunnels where a local collapse of the structure could have catastrophic consequences, e.g. immersed tunnels or tunnels which can cause the collapse of important neighbouring structures, shall ensure a sufficient level of fire resistance.	♦ Structural lining to have sufficient fire resistance.

Table B2 – Spatial Requirements from DMRB 2.2.9 – BD 78/99 – Design of Road Tunnels

Issue	Requirement	Implication for Forth Crossing
Safety Niches (Emergency Points)	**3.12 *Emergency Points*: Tunnel structures shall accommodate emergency points at intervals along the tunnel. Such points shall be large enough to house fire-fighting facilities and emergency roadside telephones connected to remote, permanently manned, police or tunnel control centres. The spacing of emergency points is determined by the requirements for spacing of emergency telephones, and fire hose reels and hydrants which shall be determined in consultation with the fire authority. The nominal spacing for emergency points is 50m, with emergency roadside telephones and fire hose reels (if fire brigade require) at every emergency point and hydrants at alternate points (ie at 100m intervals).**	♦ Safety niches at nominal intervals of 50 metres. ♦ Equipped with emergency telephones and fire fighting equipment.
Lay-bys	3.13 *Vehicle Refuges for Tunnel Incidents*: The initial cost of providing additional traffic space in the tunnel cross section to cope with incidents and breakdowns must be balanced against the operational needs of communications, surveillance, stand by recovery facilities, consequence of traffic delays and pressure on the surrounding road network. Such factors will depend on the length of tunnel, its location (rural, mountain, urban, sub aqueous) and on traffic demand. Advice from those experienced in the management of risks in road tunnels, rather than accident statistics, shall be sought to define the need for any additional traffic standing space.	♦ In a TBM tunnel, construction of lay-bys would be prohibitively expensive so the tunnel width would provide a large enough envelope for the traffic to pass a stranded vehicle at low speeds.

Emergency Lanes	3.14 *Emergency Stopping Lanes*: Due to the high costs involved there are very few examples of continuous emergency stopping lanes within tunnels. However, additional lane width or widened verges provide a temporary expedient for traffic to be able to pass a stranded vehicle. Such temporary provisions shall not be a basis for justifying traffic throughputs during prolonged periods of tunnel restriction. The first priority and whole basis of safe tunnel operation must always be to remove, as a matter of urgency, any obstacle to unrestricted lane use.	♦ The cost of providing an emergency stopping lane would be prohibitively expensive so the total width of tunnel (including verges) would allow a stranded vehicle to be passed at a slow speed by two lanes of traffic.
Emergency Walkways	**3.15 *Emergency Walkways*: Unobstructed pedestrian access, at low level, to emergency points shall be provided. [The high raised and protected walkways, which originated from the circular profiles of TBM (tunnel boring machine) constructed tunnels, give rise to distinct disadvantages: the loss of temporary standing for stranded vehicles; for drivers, the unwelcome side wall effect (avoidance) influencing driver behaviour; restricting the nearside opening of doors of stranded vehicles; loss of ready access to the emergency points and cross tube connections for all tunnel users, especially the disabled. Maintenance is also more problematical (eg duct walls, rapid deterioration of hand railing and general cleaning difficulties)].**	♦ Emergency walkways required on both sides of the carriageway.
Turning Bays	3.19 *Turning Bays*: In tunnels of over 5 km length, turning bays of sufficient size to enable a lorry to turn around shall be provided, not more than 1 km from the middle of the tunnel.	♦ Table 3.1 of the same document states that this requirement is to be determined by the Tunnel Design and Safety Consultation Group. ♦ Due to the prohibitive cost associated with construction of a turning bay, it is not considered feasible for the Forth crossing.

Headroom and Clearance	**4.25 All equipment in a road tunnel shall be placed outside of the equipment gauge. The equipment gauge for a road tunnel is determined by the traffic gauge (the theoretical clearance envelope required for vehicular traffic ie maintained headroom etc) plus, for vertical clearance, an additional allowance of 250mm. This additional clearance gives some protection to "soft" equipment, such as luminaires, from high vehicles carrying compressible loads that have passed under the portal soffit, loose ropes, flapping tarpaulins etc. Clearances shall be carefully related to carriageway and side verge widths and to the structure gauge ie the minimum "as-built" structural profile that the tunnel must achieve.** [Dimensional tolerances of bored, cut and cover and immersed tube tunnels are strongly influenced by the construction **4.26 Additional clearances to avoid damage to electrical, mechanical and communications operational equipment shall be provided as follows:** **i. 600mm horizontally from edge of kerb** **ii. Other dimensions as given in Figures 4.1 and 4.2.**	♦ The clearance envelope must allow an extra 250 millimetres above the maintained headroom that is required. ♦ Full headroom must be maintained over the first 600 millimetres of the verges/walkways on both sides. ♦ 1.0 metre wide verges/walkways are required on both sides of the carriageway. ♦ 2.3 metres headroom required for walkways.

Hard Strips	4.28 The need for provision of carriageway hard strips within a road tunnel shall be subject to a cost benefit study undertaken by the Design Organisation and considered for approval by the Technical Approval Authority of the Overseeing Organisation. 4.32 Verge widths will often be determined by the extent of provision for services beneath or the need for driver visibility. A 250mm width is needed to prevent vehicles from contacting the sides of a tunnel. The minimum verge width shall be 1.0m. The maintained headroom need be provided over only the first 0.6m of the verge as shown in Figures 4.1, 4.2 and Table 4.5.	♦ Hard strips required to maintain stopping sight distances at given design speed and horizontal radii. ♦ 1 metre wide verges required on both sides of the carriageway. ♦ Full headroom must be maintained over the first 600 millimetres of the verges/walkways on both sides.

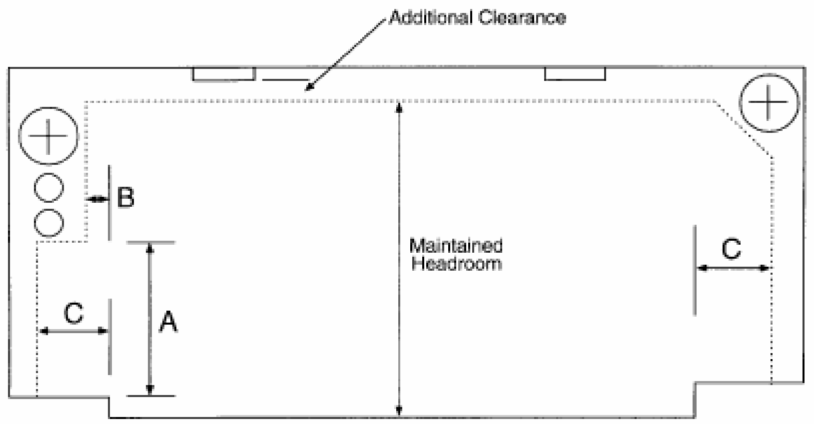


Figure 4.1 **Example Box Profile**

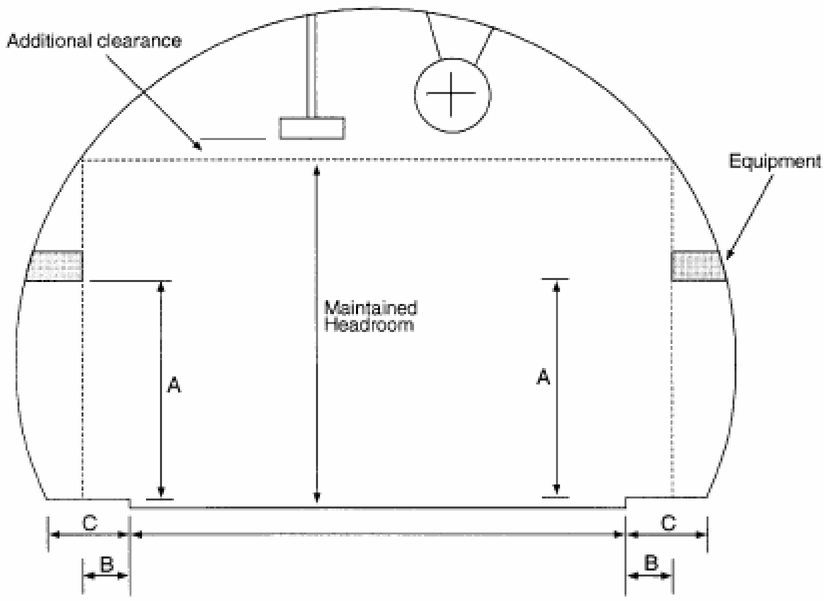


Figure 4.2 **Example Arch Profile**

Dimension	Description	Box Profile	Arch Profile
A	Walkway headroom	2300mm	2300mm
B	Width of verge with full headroom	600mm	600mm
C	Width of verge	1000mm	1000mm

Table 4.5 Minimum Dimensions (See Figures 4.1 and 4.2)

Figure B1 – Minimum Dimensions from BD 78/99

Design Speed

The design speed assumed for the tunnel is 50 miles per hour (85 kilometres per hour). This is in line with most other road tunnels, due to the fact that the cost of construction of a 60 miles per hour (100 kilometres per hour) road tunnel to meet the geometric standards of the adjacent open road would be too high. An increase in the design speed above this level would place unacceptable constraints on the horizontal alignment, as the Stopping Sight Distance (SSD) required would limit the minimum horizontal radii to a prohibitive level. SSD could be achieved by widening the hard strips and verges, but this increase in the cross sectional area of the tunnel would be disproportionately expensive, and would impact on the feasibility of a tunnel.

Road Space

Considering the traffic flow levels as predicted in recent studies, it is proposed that the tunnel would be a uni-directional twin tube tunnel made up of two dual lane carriageways, D2UM. Guidelines state that the standard lane width should be 3.65 metres. Design of an equivalent open road in accordance with DMRB 6.1.2 – TD 27/05 would include a hard shoulder or emergency stopping lane of 2.75 to 3.3 metres. However, as Clause 3.14 of BD 78/99 indicates, the high costs involved in providing this means that there are very few examples of continuous emergency stopping lanes in tunnels. Therefore, a full width hard shoulder has not been included in the design. The clause states that widened verges can provide a temporary expedient for traffic to pass a stranded vehicle. The minimum required width of the verges would be one metre.

The need for provision of narrow hard strips at the sides of the carriageway in road tunnels is based upon a cost benefit analysis type approach. In this case, hard strips are required to meet the SSD for the given design speed. The width of the hard strips is derived from the requirement to provide a temporary means for tunnel traffic to pass a stranded vehicle. TD 27/05 indicates that emergency services can make use of widths of 2.5 metres for access purposes adjacent to standard width lanes. If the stranded vehicle is positioned on the nearside verge, then a total hard strip of 1.5 metres would be sufficient for the two lanes of traffic to pass. To satisfy Clause 2.1.3 of the EU Road Tunnel Safety Regulations 2007 Consultation Draft, a total hard strip width of 1.65 metres has been assumed to provide a total width excluding normal traffic lanes, but including verges equal to a standard lane width. A minimum of approximately 0.5 metres is required for SSD, so 1.0 metre would be provided on the nearside and to 0.65 metres on the offside. This gives a total carriageway width of 8.95 metres between kerbs with one metre wide verges beyond that would also act as emergency walkways.

The vertical clearance would be determined by the maintained headroom, which is the minimum distance from the surface of the carriageway to the roof or walls of the tunnel, or any services that are suspended from the roof, plus an additional allowance of 250 millimetres to avoid damage to services in accordance with Clause 4.25 of BD 78/99. Maintained headroom of 5.03 metres is required by the DMRB giving a total clearance envelope of 5.3 metres. This satisfies the requirement in the DMRB for a New Construction Headroom of 5.3 metres.

Emergency Walkways

Emergency walkway routes serve several important purposes:

- In the event of an emergency, to allow people to move freely down the tunnel and away from any hazards;
- In the event of a breakdown or incident, to allow users to get out of their vehicles safely and reach an emergency point;
- To allow access for emergency crews in the event of a fire or accident;
- To protect equipment; and
- To provide access for maintenance when full lane closure is not suitable.

In the event of an emergency, users must be able to move along the tunnel freely until they reach a place of safety, which in this case would be a cross passage through to the adjacent tunnel or a safety niche (emergency point). Where the users use a cross passage to escape from a fire, the offside walkway of the non-affected bore would be required to be of full width to accommodate the pedestrian movement and provide protection, as the traffic in the non-incident bore may be running without disruption.

One metre wide emergency walkways would be provided on both sides of the carriageway. They should be raised 75 millimetres from the carriageway. The walkways can occupy the same space as the verges, thereby minimising the space required within the tunnel.

Safety Niches (Emergency Points)

Safety niches (emergency points) need to be located at regular intervals to provide a place of shelter in the event of an emergency. In addition to providing shelter they would also be equipped with a telephone and fire fighting equipment. The control room could be contacted, or they could be used as the first line of defence for fighting a fire.

The EU Road Tunnel Safety Regulations 2007 Consultation Draft indicates that the safety niches can consist of a box on the sidewall, or preferably a recess in the sidewall, that contains at least an emergency telephone and two fire extinguishers. The intervals that they are provided at should not exceed 150 metres with hydrants at a maximum of 250 metre intervals.

BD 78/99 states that the spacing of the safety niches should be determined in consultation with the emergency services. The nominal spacing for emergency points would be 50 metres with emergency roadside telephones and fire hose reels (if required) at every point and hydrants at alternate points.

The spacing of safety niches is recommended to be 100 metres. They would be arranged to coincide with the location of the emergency cross passage tunnels.

Lay-bys

Lay-bys are recommended in the EU Road Tunnel Safety Regulations 2007 Consultation Draft. However, it proposes an alternative to provide a total width of tunnel which is accessible to vehicles, excluding normal traffic lanes, that is equal to the width of one normal lane. This provides enough space for two lanes of traffic to pass a stranded vehicle at low speeds.

BD 78/99 indicates that the cost of providing lay-bys should be considered against a number of other factors, including the level of surveillance and stand-by emergency facilities provided, and the general conditions of a particular tunnel and its environment.

Construction of lay-bys in a Tunnel Boring Machine (TBM) tunnel is very expensive, as they are outside of the circular shape of the TBM and the tunnel lining. The total width of the proposed tunnel, including verges, would be sufficient to allow access for emergency services to an incident next to two lanes of traffic. It also enables two lanes of traffic to pass a stranded vehicle at low speeds.

Given that the safety requirements are satisfied by providing a road space of 8.95 metres, lay-bys have been omitted.

Development of Cross Section

The vehicle clearance envelope was developed, based on the road space requirements derived from the EU Road Tunnel Safety Regulations 2007 Consultation Draft and the DMRB. The dimensions are summarised in the table below.

Element	Space (m)	Total Space (m)
Horizontal		
Carriageway	2 x 3.65 = 7.30	**10.95**
Nearside hard strip	1.00	
Offside hard strip	0.65	
Total Carriageway Width	8.95	
Nearside Verge/Walkway	1.00	
Offside Verge/Walkway	1.00	
Vertical		
Maintained Headroom	5.03	**5.3**
Additional Clearance	0.25	

Along with the road space requirements, the ventilation and other services need to be accommodated in the tunnel cross section. It is anticipated that both a fresh air supply and a smoke/exhaust duct would be required for the full length of the tunnel. The size of the ducts would be determined in the detail design, but it is envisaged that a cross sectional area of approximately 10 metres squared would be required for exhaust and five metres squared for fresh air.

For the TBM tunnel, the fresh air supply would be under the road deck, along with the majority of the other services, including, but not limited to, electrical, drainage, and communications. The exhaust duct and fans would be suspended from the roof of the tunnel above the vehicle envelope. The arrangement for a Sprayed Concrete Lining (SCL) tunnel would be similar. However, given the nature of this tunnelling method there is considerable flexibility available in the shape of the tunnel, and therefore position of the services.

In an Immersed Tube tunnel, the fresh air supply would be located in cells on the outside of the main traffic space. The exhaust duct and other services would be in a central cell between the two traffic cells.

Road Gradient

The penalties for steeper gradients are more severe in tunnels than on open roads. They include higher ventilation costs, due to higher vehicle emissions and reduced traffic speeds, possibly to unacceptable levels depending on the percentage of Heavy Goods Vehicles (HGVs). A climbing lane is not practical in a tunnel due to the high costs involved in the construction. The safety of the tunnel would be compromised as vehicles moving downhill would inevitably increase speed on higher gradients and, conversely, as vehicles, particularly HGVs, slow on the uphill side there would be increased overtaking leading to an increased risk of accidents. The environmental effects of the increased fuel usage and emissions also need to be considered.

The EU Road Tunnel Safety Regulations 2007 Consultation Draft specifies that the gradient of a new road tunnel should not exceed five per cent, but that any tunnel with a gradient higher than three per cent would need additional and/or reinforced measures to enhance safety. These should be decided on the basis of a risk analysis.

The DMRB suggests that four per cent gradient should normally be regarded as the absolute maximum for an open motorway; however, an economic assessment of the effects of increasing the gradient should be carried out.

The gradient of the tunnel was constrained by the need to maintain a minimum of two diameters of cover above the TBM tunnel under the Forth. A key feature of the crossing is the deep channels which extend to depths of approximately 30 metres below sea level. Therefore, the TBM tunnel under the Forth would be approximately 20 to 25 metres below bed level across the Firth. The profile must then rise to meet network connections at the A90, M90 and M9, depending on the alignment. These connections are of the order of 60 metres above sea level, in some cases, with the topography rising to approximately 80 metres between the Firth and the connection points. Locating the toll plaza (if required) on the southern side of the Firth also means that the road must rise to the surface at an earlier stage.

The preliminary designs have endeavoured to keep the gradient at less than three per cent. However, this was not possible in all instances, particularly on Corridor D. The maximum gradient used in this case is four per cent. The additional safety measures that may be required to allow this gradient to be used could include:

- Enhanced ventilation (up to and including additional ventilation shafts and plant);
- Reduction in tunnel vehicle speed and/or traffic volume to reduce risk of congestion; and
- Control and limitation of the number and type of HGV using the tunnel.

The regulations are in consultation at present, and due for implementation during 2007. However, the current text of the regulations forms the basis for the alignment concepts presented in this report. At this stage of the design process it is difficult to assess the cost impact of the steeper gradient. However, it is anticipated that it would not be prohibitive. Should this option be carried forward the design would be optimised to find a balance between the reduced costs of a shorter, steeper tunnel alignment and the increase in safety measures that may be required.

Drainage and Crossfall

BD 78/99 recommends that a minimum crossfall of 2.5 per cent is provided throughout the tunnel. The crossfall is required for drainage purposes resulting from inflow of rainfall at the portals, groundwater seepage through the roof and walls, accidental spillage and cleaning up afterwards, routine wall washing and fire fighting.

A superelevation may be required to provide comfortable levels of lateral acceleration for certain degree of horizontal curvature.

The drainage system would consist of road gulleys and longitudinal drains feeding sumps which are discharged by pumps to the stormwater drainage system via an interceptor to separate the pollutants from spillages. The drainage system would be located under the carriageway surface. Sumps are usually located close to the portals to catch the water flowing down the approach ramps, and prevent it from entering the tunnel. In addition, sumps are located at the low point in the tunnel. With the possibility of flammable liquid flowing into the drainage system, a combustible gas detection system would be provided in the sumps, sometimes with an automated foam extinguishing system.

Fire Resistant Lining

Fire resistance of the tunnel structure is essential to reduce the damage caused by fire. This in turn reduces the possibility of failure or collapse and also minimises the time and cost of any required reinstatement. The damage would be dependent on both the fire load and the fire duration, the latter being determine by the capacity of the drainage and ventilation systems within the tunnel, the quantity of combustible material involved, and the fire fighting provisions available. Providing adequate cover to structural reinforcement and resistance to spalling of concrete is necessary to protect fire fighters from falling debris or equipment that is suspended from the roof, such as jet fans. Emergency equipment such as power and communication lines and mechanical components must also be capable of withstanding high temperatures.

For the tunnel under the Forth, the consequences of damage to the structural lining are serious: in the extreme case damage could lead to failure of the waterproofing and inundation of the tunnel.

B2.2 Intervention and Escape Routes

Introduction

The safe evacuation of users and emergency service access is of paramount importance in the design of any tunnel. Tunnel users must be able to evacuate the tunnel, without their vehicles, through an emergency escape route to a safe place. Emergency services must be able to access an incident within the tunnel both on foot and with heavy equipment. The response time of the emergency services, particularly the fire service, must be as short as possible, and would need to reach the incident unobstructed regardless of the traffic conditions. Access routes include:

- Moving down the affected bore directly to the incident from the tunnel portal;
- Using the non-affected bore to access the incident via a cross connecting passage; and
- By foot via emergency access points in the ventilation shafts on either shore.

Tunnel users evacuate the tunnel by means of similar routes.

Table B3 shows the clauses of the EU Road Tunnel Safety Regulations 2007 Consultation Draft that detail the safety requirements and emergency access/egress provisions of the tunnel. The table also details their implications for the proposed tunnel.

Table B4 shows the clauses of the BD 78/99 that list the safety features that are required. The table also details their implications for the proposed tunnel. The design must comply with the mandatory requirements of the standards which are in bold print, or a suitable Departure from Standard must be agreed with the relevant Overseeing Organisation. Where the word "shall" is used, then the requirement is expected to be carried out in full, unless, due to constraints of a particular scheme, a recorded agreement has been made with the Overseeing Organisation that another way of satisfying the intention of the requirement is to be used. The remainder contains advice to designers for their consideration.

A risk-based approach would be used to define many of the safety elements in the design. Risk analyses may be carried out at all stages of design to refine and optimise the design and operation of the tunnel. At this early, conceptual, stage it is necessary to adopt a fairly conservative approach to the interpretation of these regulations, as there is not sufficient information to carry out detailed risk assessments, and, therefore, limited opportunity to optimise the design.

The aim of concept development is, therefore, to deliver robust solutions that recognise major risk items without compromising possible future optimisation and associated cost reduction.

Table B3 – Emergency Access/Egress Requirements from EU Road Tunnel Safety Regulations 2007 Consultation Draft

Issue	Requirement	Implication for Forth Crossing
Emergency Walkways	2.3.1. In new road tunnels without an emergency lane, emergency walkways, elevated or not, shall be provided for use by tunnel users in the event of a breakdown or an accident. This provision does not apply if the construction characteristics of the road tunnel do not allow it or allow it only at disproportional costs and the road tunnel is unidirectional and is equipped with a permanent surveillance and lane closure system.	♦ Emergency Walkways to be provided on both sides of the carriageway.
Pedestrian Access and Egress	2.3.3 Emergency exits allow tunnel users to leave the road tunnel without their vehicles and reach a safe place in the event of an accident or a fire and also provide access on foot to the tunnel for emergency services. Examples of such emergency exits are: —direct exits from the tunnel to the outside, — cross-connections between tunnel tubes, — exits to an emergency gallery, — shelters with an escape route separate from the tunnel tube. 2.[illegible] [illegible] how quickly smoke travels under local conditions, shows that the ventilation and other safety provisions are insufficient to ensure the safety of road users. 2.3.6. In any event, in new road tunnels, emergency exits shall be provided where the traffic volume is higher than 2 000 vehicles per lane. 2.3.8 Where emergency exits are provided, the distance between two emergency exits shall not exceed 500 metres. 2.3.9. Appropriate means, such as doors, shall be used to prevent smoke and heat from reaching the escape routes behind the emergency exit, so that the tunnel users can safely reach the outside and the emergency services can have access to the road tunnel.	♦ Pedestrian cross passages at max 500 metre intervals.

Vehicular Access and Egress	2.4.1. In twin-tube road tunnels where the tubes are at the same level or nearly, cross-connections suitable for the use of emergency services shall be provided at least every 1 500 metres. 2.4.2. Wherever geographically possible, crossing of the central reserve (median strip) shall be made possible outside each portal of a twin- or multi-tube road tunnel. This measure will allow emergency services to gain immediate access to either tube.	♦ Vehicular cross passages at max 1500 metre intervals. ♦ Cross over facilities outside each portal.
Safety Niches (Emergency Points)	2.10.1. Emergency stations are intended to provide various items of safety equipment, in particular emergency telephones and extinguishers, but are not intended to protect road users from the effects of fire. 2.10.2. Emergency stations can consist of a box on the sidewall or preferably a recess in the sidewall. They shall be equipped with at least an emergency telephone and two fire extinguishers. 2.10.3. Emergency stations shall be provided near the portals and inside at intervals which for new road tunnels shall not exceed 150 metres and which in exiting tunnels shall not exceed 250 metres.	♦ Safety Niches to be provided at max 150 metre intervals. ♦ Safety Niches to be equipped with one emergency telephone and two fire extinguishers.

Table B4 – Emergency Access/Egress Requirements from DMRB 2.2.9 – BD 78/99 – Design of Road Tunnels

Issue	Requirement	Implication for Forth Crossing
Safety Niches (Emergency Points)	3.12 *Emergency Points*: Tunnel structures shall accommodate emergency points at intervals along the tunnel. Such points shall be large enough to house fire-fighting facilities and emergency roadside telephones connected to remote, permanently manned, police or tunnel control centres. The spacing of emergency points is determined by the requirements for spacing of emergency telephones, and fire hose reels and hydrants which shall be determined in consultation with the fire authority. The nominal spacing for emergency points is 50m, with emergency roadside telephones and fire hose reels (if fire brigade require) at every emergency point and hydrants at alternate points (ie at 100m intervals).	♦ Safety niches at nominal intervals of 50 metres. ♦ Equipped with emergency telephones and fire fighting equipment.
Emergency Walkways	3.15 *Emergency Walkways*: Unobstructed pedestrian access, at low level, to emergency points shall be provided. [The high raised and protected walkways, which originated from the circular profiles of TBM (tunnel boring machine) constructed tunnels, give rise to distinct disadvantages: the loss of temporary standing for stranded vehicles; for drivers, the unwelcome side wall effect (avoidance) influencing driver behaviour; restricting the nearside opening of doors of stranded vehicles; loss of ready access to the emergency points and cross tube connections for all tunnel users, especially the disabled. Maintenance is also more problematical (eg duct walls, rapid deterioration of hand railing and general cleaning difficulties)].	♦ Emergency walkways required on both sides of the carriageway.

Pedestrian Access and Egress	**3.16 *Escape Routes*: In twin bore tunnels, passenger escape routes through fire doors positioned in central walls or cross-connecting passages, shall be provided. These shall be positioned at 100m nominal intervals and provided with permanently lit signs, emergency roadside telephones etc. Single bore tunnel escape route and safe refuge requirements shall be examined and established by the Design Organisation from first principles, to the agreement of the TDSCG. See Chapters 5, 8 and Appendix D for additional** 3.17 *Tunnel Cross Connections*: Tunnel cross-connections are generally of three types: i. A single set of fire doors in the partition wall between two traffic bores. ii. A cross passage with fire doors at both ends providing a safe refuge and an escape route from one bore to the other. iii. Access doors to a central escape shaft or passage, leading to a safe exit. The second and third types above require ventilation to maintain a supply of fresh air to the escape route and positive pressure or other provisions to exclude smoke from any fire within a traffic bore. Where two or more bores are linked by cross connections, the effect of opening one or more of those cross connection doors shall be considered in both normal and emergency situations. The design shall incorporate features which reduce or eliminate any hazard caused by the opening of such a cross connection.	♦ Pedestrian cross passages required at 100 metres nominal intervals. ♦ Fire doors required for the cross passages. ♦ Ventilation required for the cross passages to maintain a supply of fresh air and a positive pressure to exclude smoke from a fire in the traffic bore.

Vehicular Access and Egress	3.18 *Vehicle Cross Overs*: Vehicle cross overs shall be provided on tunnel approaches to enable contra flow working in twin bore tunnels, or convoy working (see TA63 DMRB(8.4.5)) in single bore tunnels for maintenance etc. If there is a junction near the tunnel, care shall be taken to ensure that all traffic can use the cross overs. Care shall also be taken with sight lines through cross-overs, particularly those adjacent to widely spaced twin bores and provision made for suitable temporary or permanent signing, including any necessary speed limit signs. During normal operation, suitable means of preventing vehicles from crossing from one carriageway to the other shall be provided to avoid a safety hazard. Movable or demountable barriers, when implementing contraflow operation, shall be evaluated in terms of possible reductions in maintenance costs.	♦ Cross over facilities outside each portal. ♦ Movable or demountable barriers required at the crossovers.

Pedestrian Cross Passages

The most common form of escape routes used in road tunnels is escaping to the adjacent tunnel by means of cross-connecting tunnel passages. A schematic layout of this configuration is shown in Figure B2.

BD 78/99 requires passenger escape routes through fire doors located in either the central walls or cross connecting passages to be located at 100 metre nominal intervals. The passages have fire doors on both sides, and are pressurised to prevent inflow of smoke or fumes during an emergency. In an emergency, traffic is typically prevented from entering both tunnels. The non-incident tunnel is then cleared of traffic to allow access by emergency services. Emergency vehicles may also enter the affected tunnel. During this time the ventilation system manages smoke to assist evacuation. Tunnel users escape via the cross passages into the adjacent tunnel bore.

The EU Road Tunnel Safety Regulations 2007 Consultation Draft states that, where emergency exits are provided, the distance between two emergency exits shall not exceed 500 metres.

Construction of the cross passages is a complex and expensive operation, particularly in a TBM tunnel, as a different method of excavation must be used. European standards generally prescribe a spacing of 200 metres or more. It is therefore recommended to provide pedestrian cross passages at 200 metre intervals.

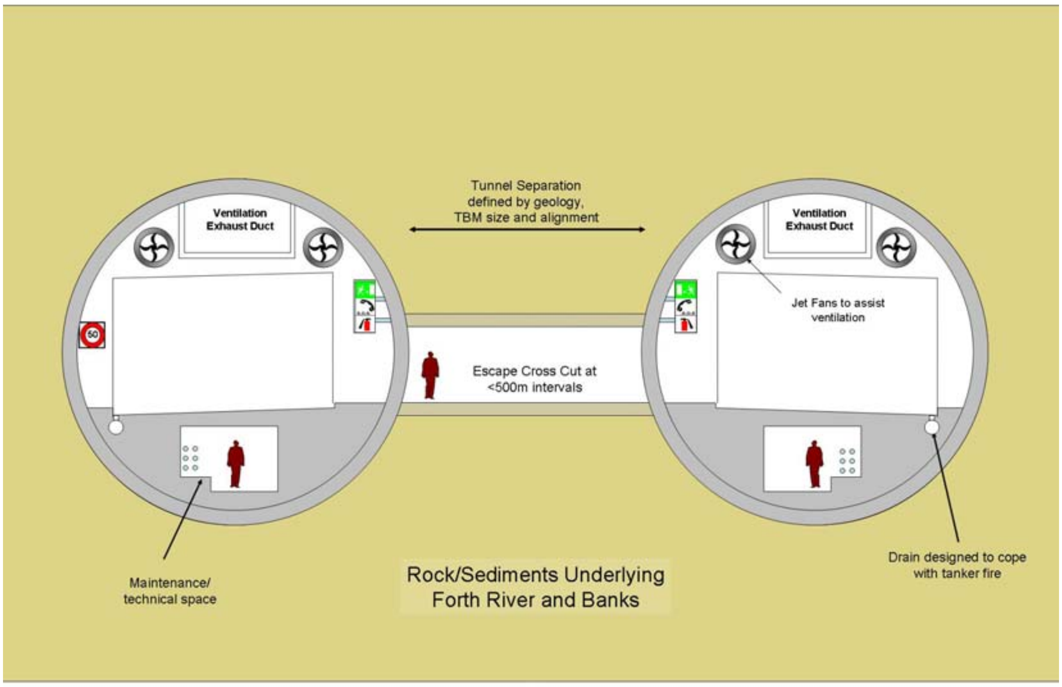


Figure B2 – Schematic of Bored TBM tunnel using cross passages as escape routes

Vehicle Cross Passages

Vehicle cross passages provide direct access between the two bores for use by emergency vehicles to gain access to an incident from the non-affected bore. This allows the emergency services to bring all the necessary heavy fire or intervention equipment directly to the incident, and evacuate injured people by vehicle. Smoke free conditions are maintained in the cross passages to facilitate safe and speedy evacuation, and to ensure that the non affected bore is kept clear of smoke during a fire. The air-flow in the direction of the incident tube would be significantly increased to maintain a positive pressure to exclude smoke from the passage. In addition, a 'bubble-effect' would be generated in the incident tube, where the fresh air jet clears the smoke in the vicinity of the cross-passage door. The doors in the region of the fire are opened either manually by escaping passengers or staff, or via remote control from the Tunnel Control Centre.

The EU Road Tunnel Safety Regulations 2007 Consultation Draft states that vehicle cross passages must be provided at intervals not exceeding 1,500 metres. It is recommended to provide vehicle cross passages at 1,400 metre intervals so the arrangement fits in with the spacing of the pedestrian cross passages.

Access for Emergency Services

Vehicle cross passages of adequate size to allow access by emergency vehicles would be located at intervals of 1,400 metres, satisfying the requirements set out in EU Road Tunnel Safety Regulations 2007 Consultation Draft. Both the EU regulations and BD 78/99 require provisions for crossing of the central reserve outside each portal of a road tunnel to allow emergency services to gain immediate access to either tube. Emergency access on foot would also be provided at approximate quarter points of the tunnel on each shore at the ventilation shafts.

Shaft Access to and from Ground Level

The provision of regular access/egress points from the tunnel to the surface would increase its safety performance. However, given that the tunnel is under the Forth for the majority of its length, this cannot be achieved. However emergency access and egress points could be located at each shore at the ventilation shafts. These exits would be used for evacuation of tunnel users by foot and access for the emergency services by foot. Both staircases and lifts could be provided within the shafts.

B3 TUNNEL SERVICES

B3.1 Introduction

The following section details the requirements for services in the tunnel. Mechanical and electrical services play an important role in the safe operation of the tunnel. The level of mechanical and electrical services provided has a large impact on the operating costs of the tunnel.

Table B5 shows the clauses of the EU Road Tunnel Safety Regulations 2007 Consultation Draft that detail the service requirements for road tunnels. The table also details their implications for the proposed tunnel.

Table B5 – Service Requirements from EU Road Tunnel Safety Regulations 2007

Issue	Requirement	Implication for Forth Crossing
Drainage	2.6.1. Where the transport if dangerous goods is permitted, the drainage of flammable and toxic liquids shall be provided for through well-designed slot gutters or other measures within the road tunnel cross sections. Additionally, the drainage system shall be designed and maintained to prevent fire and flammable and toxic liquids from spreading inside tubes and between tubes.	♦ Design brief is to replicate service offered by existing bridge. Existing bridge allows certain dangerous goods, therefore the tunnel would be designed in a similar manner.
Lighting	2.8.1. Normal lighting shall be provided to ensure appropriate visibility day and night for drivers in the entrance zone as well as in the interior of the road tunnel. 2.8.2 Safety lighting shall be provided to allow a minimum visibility for tunnel users to evacuate the tunnel in their vehicles in the event of a breakdown of power supply. 2.8.3. Evacuation lighting, such as evacuation marker lights, at a height of no more than 1.5 metres, shall be provided to guide tunnel users to evacuate the tunnel on foot, in the event of emergency.	♦ Lighting to be provided for normal and emergency use. ♦ Evacuation lighting to be provided.
Ventilation	2.9.1 The design, construction and operation of the ventilation system shall take into account: — the control of pollutants emitted by road vehicles, under normal and peak traffic flow, — the control of pollutants emitted by road vehicles where traffic is stopped due to an incident or accident, — the control of heat and smoke in the event of a fire. 2.9.2. A mechanical ventilation system shall be installed in all road tunnels longer than 1 000 metres with a traffic volume higher than 2 000 vehicles per lane. 2.9.3. In tunnels with bi-directional and/or congested unidirectional , longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals. 2.9.4. Transverse or semi-transverse ventilation systems shall be used in road tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed under point 2.9.3. These systems must be capable of evacuating smoke in the event of a fire.	♦ Mechanical ventilation system required to control level of pollutants from vehicles and heat and smoke from a fire. ♦ Semi transverse or fully transverse system required. ♦ System must be capable of evacuating smoke in the event of a fire.
Water Supply	2.11 A water supply shall be provided for all road tunnels. Hydrants shall be provided near the portals and inside at intervals which shall not exceed 250 metres. If a water supply is not available it is mandatory to verify that sufficient water is provided otherwise.	♦ Fire hydrants required at max 250 metre intervals.
Control Centre	2.13.1. A control centre shall be provided for all road tunnels longer than 3 000 metres with a traffic volume higher than 2 000 vehicles per lane.	♦ Dedicated Tunnel Control Centre required.

Monitoring	2.14.1. Video monitoring systems and a system able to automatically detect traffic incidents (such as stopping vehicles) and/or fires shall be installed in all road tunnels with a control centre.	♦ Automatic traffic incident detecting monitoring system required.
Communication Systems	2.16.1. Radio re-broadcasting equipment for emergency service use shall be installed in all road tunnels longer than 1 000 metres with a traffic volume higher than 2 000 vehicles per lane. 2.16.1. Where there is a control centre, it must be possible to interrupt radio re-broadcasting of channels intended for tunnel users, if available, in order to give emergency messages.	♦ Radio re-broadcasting equipment required.
Power Supply and Electrical Circuits	2.17.1. All road tunnels shall have an emergency power supply capable of ensuring the operation of safety equipment indispensable for evacuation until all users have evacuated the road tunnel. 2.17.2. Electrical, measurement and control circuits shall be designed in such a way that a local failure, such as one due to a fire, does not affect unimpaired circuits.	♦ Uninterruptible power supply required. ♦ Electrical equipment to be fire resistant.

B3.2 Tunnel Ventilation

General Considerations

BD 78/99 requires ventilation systems to be designed to:

- Supply sufficient fresh air to all parts of the tunnel;
- Maintain vehicle exhaust pollutants within prescribed limits;
- Provide a hazard free environment for tunnel users, the local community, and any amenities likely to be affected by the discharge of fumes from the tunnel; and
- Control smoke and heat in the event of a fire in a tunnel, and direct it away from tunnel users while they escape, whilst also providing cool fresh air for fire fighters tackling the blaze.

The main considerations for normal operation ventilation would be the traffic flows, particularly the percentage of HGVs, and the length, depth, cross sectional dimensions, and other road geometry (particularly the vertical gradients). The ventilation design arrangement would be influenced by the operation method proposed, the tunnel maintenance and emergency intervention procedures, including where and how emergency intervention teams gain access and supervise emergency escape.

Typical Ventilation Systems

There are three main types of ventilation systems for normal and emergency operations: longitudinal, semi-transverse, and fully transverse ventilation. A combination of these methods is also possible to suit the conditions of a particular tunnel.

Longitudinal

The basic principle of longitudinal ventilation system is to push the air in the traffic direction until reaching an extraction zone or the tunnel portal. The pollutants are diluted only by the incoming fresh air at the tunnel portal. The ventilation equipment is usually jet fans. The fans blow the pollutants along the tunnel aided by the piston effect of the moving traffic. It is therefore only suited to uni-directional tunnels. As pollution is generated by vehicles all along the tunnel, pollutant concentration increases along the tunnel. If similar types of vehicle traffic use the tunnel and travel at constant speeds, the pollutant concentration can be expected to increase linearly. Therefore the practical length for using longitudinal ventilation is limited. Longer tunnels can be split into sections by providing intermediate inlet and discharge shafts along the length of the tunnel.

In emergency situations longitudinal ventilation can only push (or pull) the smoke. By fan reversal and the use of ventilation shafts, the smoke can be isolated to a section of the tunnel. However, this still relies on smoke travelling in the tunnel environment, and, therefore, may affect people evacuating and the emergency services. The time needed for the fans to reverse also leads to smoke clogging of the tunnel.

Generally longitudinal ventilation is the most economic type of system, since it places the smallest burden on fans, and does not require air ducts. Operating costs can become significant if the fans are required to run continuously. However, the use of natural ventilation from the piston effect of the traffic should be maximised and supplemented by jet fans for short periods. Figure B3 taken from BD 78/99 shows a schematic representation of a longitudinal ventilation system.

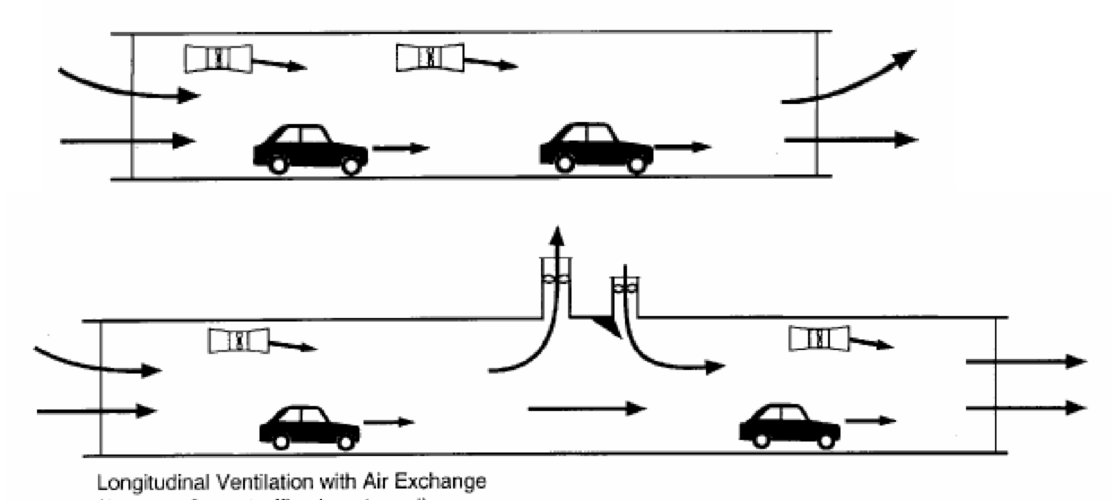


Figure B3 – Longitudinal Ventilation System from BD 78/99

Semi-Transverse

The basic principle of the semi-transverse ventilation system is to perform a local dilution of pollutants by introducing fresh air through a supply duct for the whole length of the tunnel. The complete traffic space acts as the exhaust duct discharging at the portals or through intermediate extraction shafts. This implies increasing the ventilation flow rate towards the exit portal as pollutant levels increase. This results in an almost constant pollutant concentration along the tunnel. In the centre of the tunnel where flows are lowest, there can be a locally high concentration, again combated by locally increasing the fresh air supply. This is achieved by baffle plates or dampers, which can be adjusted to vary the flow rate through the apertures of the inlets along the supply duct. The passage of air in the tunnel may be assisted by fans.

In the event of a fire in the tunnel, the fresh air supply duct can be turned into a smoke extraction duct by reversal of the supply fan system. Similar to the longitudinal system, it takes time for the supply fans to be reversed and extract the smoke from the traffic space. This may lead to smoke convection destratification problems. Figure B4 taken from BD 78/99 shows a schematic representation of a semi transverse ventilation system.

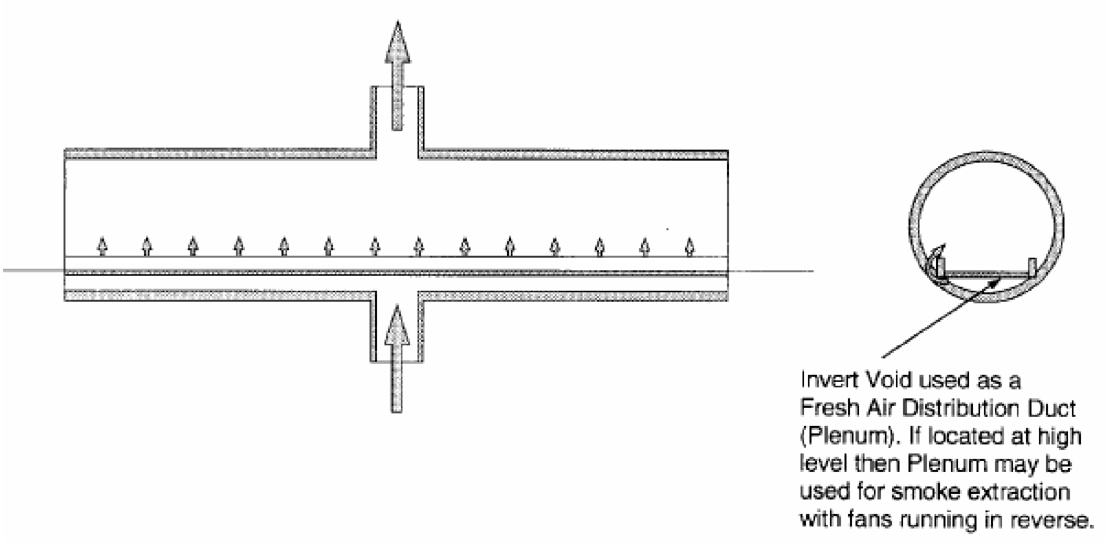


Figure B4 – Semi Transverse Ventilation System from BD 78/99

Fully Transverse

This is the most comprehensive form of mechanical ventilation. It has the highest capital and operational costs. Fully transverse ventilation is based on the same general principals as a semi-transverse system. However, separate fresh air supply ducts and exhaust ducts are provided with separate fan systems. The fresh air supply is usually provided from a duct beneath the roadway, and the exhaust duct is suspended from the roof of the tunnel. The air therefore travels vertically from the invert to crown of the tunnel along its complete length, with little longitudinal flow.

Pollution is effectively removed at source, given that vehicle exhaust is buoyant until cooled. In the event of a fire, no fan reversal is required and the smoke is extracted directly, aided by its buoyancy. The fresh air supply can be cut off as required and the longitudinal spread of smoke and hot gases is effectively limited. Figure B5, taken from BD 78/99, shows a schematic representation of a fully transverse ventilation system.

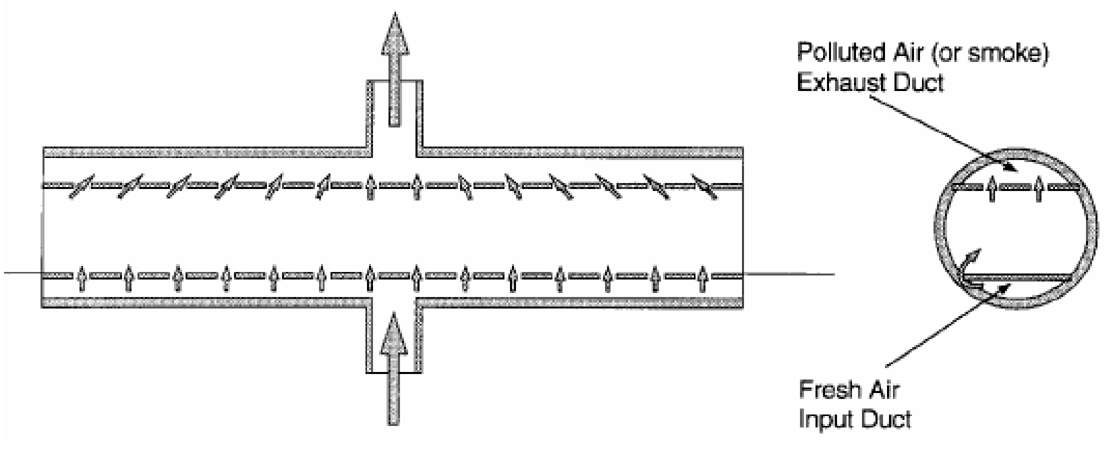


Figure B5 – Fully Transverse Ventilation System from BD 78/99

Implications for the Forth Crossing

The EU Road Tunnel Safety Regulations 2007 Consultation Draft indicates that for a tunnel such as the proposed replacement Forth Crossing, a semi transverse or fully transverse ventilation system is required. The system should be capable of evacuating smoke in the event of a fire. The implications of this are that, at very minimum, a fresh air supply duct is required for the full length of the tunnel. Preliminary investigations indicate that a duct in the region of five metres squared is needed. If a fully transverse system is specified, a smoke/exhaust duct would be required for the full length of the tunnel. Initial examinations indicate that a cross sectional area of approximately 10 metres squared is required. For a bored TBM tunnel, the fresh air supply would be located under the road deck. The exhaust duct and fans would be suspended from the roof of the tunnel above the vehicle envelope. The arrangement for a mined SCL tunnel would be similar. In the immersed tube tunnel, the fresh air supply would be located in the side cells and the exhaust in the central cell between the two carriageway spaces.

The length of the three proposed tunnel alignments varies from 6.5 kilometres to 8.5 kilometres approximately. Therefore, it is recommended that a fully transverse system is adopted with ventilation shafts at approximate quarter points on both banks for both fresh air intake and exhaust. The concentration of pollutants would be too high to discharge directly at the portals and, in any case, the length of the tunnel means that intermediate ventilation stations are required.

The length of the tunnel, combined with its sub-aqueous location under the Forth, mean that safety is of paramount importance. A fire in the tunnel at a mid-river location may leave trapped users feeling disorientated and panicky, so it is imperative that the best ventilation system is in place to provide some reassurance to users, and assist in their safe evacuation and the speedy delivery of the emergency services.

At detail design stage, the design of the ventilation system could be optimised so that a cheaper system is developed, or a combination of systems adopted. An example of this might be to provide a fully transverse system under the Firth between the ventilation shafts. At mid-river the longitudinal air flow in the traffic space would be minimal, but increasing progressively towards the exhaust shafts. The end sections of the tunnel could then have a longitudinal ventilation system with jet fans fed by fresh air intake at the ventilation shafts.

Pollution Control

The levels of pollution both within the tunnels and around the ventilation exhausts would be determined by mathematical modelling, taking into account the external environmental conditions. The pollution load of the air in the tunnel generally increases with tunnel length, and particularly in regard to the gradient of the tunnel and the percentage of heavy goods vehicles. Normal operation of ventilation equipment is by remote sensing of the pollution concentrations and visibility levels.

At the portals, high central walls are usually provided to reduce the recirculation of polluted air from the exhausting bore to the other. The predicted effect of emissions from the tunnel traffic on the external ambient conditions needs to be assessed. Where the portal emissions must be limited, ventilation extract shafts can be introduced to increase dispersal. The dilution and dispersal of emissions is spread out over a greater outfall height and distance, given that vehicle exhaust and fire smoke are buoyant until cooled. The fresh air intake is located close to the ground level, so that fresh air is drawn in horizontally.

BD 78/99 gives pollution limits for the tunnel interior. The figures are based on Permanent International Association of Road Congresses (PIARC) 1995: Road Tunnels: Emissions, Ventilation and Environment, and Health and Safety Executive (HSE) document EH40: Occupational Exposure Limits. Recommendations are for short term exposure of 15 minutes or less based on congested traffic conditions in the tunnel:

- Carbon Monoxide (CO): 200 parts per million (ppm);
- Nitric Oxide (NO): 35 ppm; and
- Nitrogen Dioxide (NO_2): 5 ppm.

Detectors are installed in the tunnels to monitor and control the air quality at all times. These include CO and NO detectors within the tunnel and NO_2 detectors at the portals. The visibility inside the tunnel is measured using a transmissometer which measures light transmittance.

Ventilation of Emergency Access and Escape Routes

BD 78/99 requires that ventilation is provided to the emergency access and escape routes. For the proposed tunnel under the Forth, this implies the cross passages and the non-affected traffic bore. Smoke free conditions are maintained in the cross passages and the non-incident bore to ease safe and speedy evacuation of tunnel users, and uninhibited access for the emergency services. The air flow in the direction of the incident tube can be significantly increased to maintain a positive pressure to exclude smoke from the passage. In addition, a 'bubble-effect' is generated in the incident tube, where the fresh air jet clears the smoke in the vicinity of the cross-passage door. The doors in the region of the fire would be opened either manually by escaping passengers or by staff, or via remote control from the Tunnel Control Centre (TCC).

B3.3 Safety Controls and Equipment

Detection, Information and Control

Tunnel Control Centre

The EU Road Tunnel Safety Regulations 2007 Consultation Draft requires all tunnels greater than three kilometres long with more than 2,000 vehicles per day to have a dedicated TCC. It is likely to be located within the toll plaza complex, should one be required. This centre would be responsible for monitoring the tunnel at all times, traffic management, traffic information communication, and signal control.

Monitoring and Supervision

The tunnel should be provided with Supervisory Control and Data Acquisition system (SCADA) in accordance with BD 78/99. The aim of the SCADA system is to ensure a safe environment for tunnel users in a multitude of operating conditions. It provides real time status of traffic conditions and operations of all mechanical and electrical installations. This enables the TCC to optimise conditions and parameters remotely, while the system aids the optimisation process.

Telephones

Telephones are positioned away from tunnel traffic at a height of 1.1 metres above ground level to ensure safe and practical use. They are used for emergency, maintenance and smoke control. The TCC is automatically alerted when the hand set is lifted. Adjacent telephones are served by independent cables to reduce the risk of total system failure. Signage allows users to easily locate the nearest emergency telephone. Maintenance and smoke control telephones are installed in the safety niches. The latter connect the user directly to the ventilation controller.

Radio Broadcasting

Radio systems are provided within the tunnel to maintain communication with maintenance staff on a day to day basis and with emergency personnel in the event of an incident. Radio systems should adhere to the following priority list:

- Police;
- Fire Brigade;
- Ambulance Services;
- Tunnel operating Authority; and
- Other Services.

Police services and fire brigades use UHF and VHF frequencies for communication within the tunnel which allows the same degree of contact when above ground. Car radio and mobile phones would normally cease to operate effectively once users enter the tunnel. However, the public radio system allows re-broadcasting of selected public radio stations and mobile phone signals where provided. The tunnel operators can break into these broadcasts to give information or instructions to drivers during incidents supplementing messages shown on variable message signs.

Closed Circuit Television (CCTV)

CCTV is installed on approach roads, at tunnel portals, and within the tunnel itself, providing comprehensive unobstructed coverage of the tunnel. The automatic incident detection system, CCTV Alert, is used to feed information to the TCC identifying the nature, cause, and severity of incidents that occur. CCTV Alert would automatically detect the following incidents:

- An object on the roadway;
- A vehicle stopping on the carriageway;
- Pedestrian movement;
- Variations in speed above and below desired thresholds; and
- Fire in the tunnel.

CCTV Alert is also linked to the cross passage doors and fire points through SCADA allowing the cameras to focus on these locations to allow a quick assessment of potential emergency situations.

Signs and Signals

Variable Message Signs (VMS) are utilised to control traffic during maintenance and emergency closures. They are controlled from the TCC. Lane control signals allowing separate indication for each traffic lane are located at portal entrances and within the tunnel. They are mounted centrally above the running lanes. Conventional traffic signs and Variable Speed Limit (VSL) signs are positioned on all approach routes and at appropriate intervals within the tunnel. Escape routes should be adequately signed. A sign showing the distance to the nearest emergency exit is displayed at each safety niche (emergency point).

Over Height Detectors

Detection loops for over height vehicles on the approaches to the portals are usually provided. They are linked to VMS and specific traffic management plans that are implemented to alert the driver of an offending vehicle, and to divert it from the tunnel. If the over height vehicle continues en-route to the tunnel an automated barrier closes the tunnel and traffic signals turn to red.

Fire Fighting Facilities

Fire Extinguishers

Each safety niche would contain dry powder and aqueous film forming foam fire extinguishers. This apparatus satisfies fire rating as outlined in BS EN 3 Part 1, and facilitates initial intervention by road users or operating team.

Fire Fighting System

Tunnel fire fighting systems consist of:

- Fire water tanks;
- Two fire extinguishers at each safety niche;
- One pressurised fire main in each tunnel bore; and
- Fire hydrants with hose reels at alternate safety niches.

Fire Main

The fire main is required to comply with local authority and fire brigade requirements. Each fire main is sourced from an independent water source to ensure security of supply. The main is protected against freezing using thermal insulation. The EU Road Tunnel Safety Regulations 2007 Consultation Draft specifies a maximum hydrant spacing of 250 metres. In the proposed Forth tunnel, it is anticipated that they would be provided in alternate safety niches, i.e. 200 metre intervals. Hydrants are positioned 750 millimetres above the walkway or verge and are suitable to use with hoses that satisfy BS 3169.

Hose Reels

BD 78/99 requires the hose reels to be long enough to enable discharges from adjacent hoses to overlap. The water pressure within the hose should satisfy BS EN671-1:1995 and pressure reducing valves are provided to decrease the water pressure as it comes from the fire main. Lifting the hose off the reel automatically starts the flow of water into the hose and a nozzle valve controls the water jet.

B3.4 Other Equipment

Drainage

Road gullies should be provided at a maximum spacing of 20 metres. These are connected to longitudinal drainage pipes which in turn feed into sumps. Drainage sumps and pumps are provided to collect water from the road surface and discharge it safely. The sumps located near the tunnel portal intercept storm water from the approach ramps via gullies. Sumps are also located at low points within the tunnel to collect run off from the following sources:

- Ground water seepage;
- Tunnel washing;
- Use of fire hydrants; and
- Spillages from vehicles.

Scotland is subject to snowfall so an allowance should be made for melting water from snow and ice being brought into the tunnel. The tunnel would have a full waterproofing system and therefore a ground water inflow of less than 1.0 litre per metres squared per day is anticipated. An interconnected series of sumps has sufficient capacity to contain an adequate volume of drainage water. Interceptors to collect heavily polluted runoff are also provided as the separation of petrol, oil, grease and other pollutants is required before the drainage water is discharged. The sumps are fitted with sensors which detect a build up of common hydrocarbons and immediately commence protective measures. Sumps are not located adjacent to control rooms due to the risk of explosion. A pumped system transfers the water through twin rising mains passing along the tunnel below the road deck. It eventually discharges into the local stormwater drainage system.

Lighting

Tunnels require a high standard of lighting to allow traffic to traverse with the same speed, degree of safety and visibility as allowed by the approach roads. Lighting also reduces the claustrophobic effect commonly experienced by tunnel users. Drivers` eyes need a short time to safely adapt from the brightness of daylight surroundings to the relatively dimly lit tunnel environment. A transition zone at the tunnel entrance provides a gradual reduction in lighting to the levels of the tunnel interior. Similarly, a provision is made at the tunnel exit to allow the driver to re-adapt to daylight.

Automatic lighting controls regulate the level of luminance in the tunnel in line with external light intensity. The discomfort known as visual flicker, caused by the fluctuating levels of brightness or colour is eliminated by placing the light fittings at correct intervals. An uninterruptible power supply ensures that sufficient lighting remains in operation at all times. The lighting layout would be optimised to keep the operating costs as low as possible while simultaneously providing a comfortable driving environment for all users. The use of reflective secondary tunnel lining also helps to reduce the power consumption as they contribute to the brightness of the tunnel by reflecting the light in a positive fashion.

Power Supply

Duplicated Power Supply

It is anticipated that two high voltage power supplies of 11kV would be required. These power supplies would be laid in separately routed cables and derived from different points on the National Grid to ensure maximum security of supply.

This supply is then transformed down to 400 volts at substations for distribution to plant and equipment. This tunnel would require two or three substations. The supply is then circulated via low voltage switchboards to distribution panels mounted on the tunnel walls at road level.

Uninterruptible Power Supply (UPS)

It can be difficult to obtain two strictly independent power supplies as they may be derived from a common 33kV level. Therefore a UPS with a two hour capacity for essential loads such as tunnel lighting, fire fighting, communications and traffic control systems should be provided. The UPS provides essential equipment with a continuous supply while a standby generator is started or while a predetermined tunnel evacuation procedure is underway.

Standby Generating Equipment

Due to the overall length of the tunnel, it is envisaged that ventilation plant would need to be operated for extended periods. The electrical load required to work the ventilation equipment is beyond the capacity of a UPS system. Therefore it is anticipated that a four hour fire protected, standby generator would be required.

B4 SAFETY MANAGEMENT

B4.1 Incident Management

The management of an incident in the tunnel is controlled by the Tunnel Control Centre (TCC). This is likely to be located within the toll plaza complex, should one be required. The centre is responsible for monitoring the tunnel at all times, traffic management, traffic information communication and signal control. The automatic incident detection system, CCTV Alert, is used to feed information to the operator in the TCC identifying the nature, cause and severity of incidents that occur. CCTV Alert can automatically detect a vehicle stopping in the tunnel in the event of a breakdown or accident and it also detects fire. Typical response time should be approximately five minutes.

Breakdowns

As per normal practice in tunnels of this length, recovery vehicles are located at each side of the tunnel adjacent to the portal and once the incident is detected by the TCC, a recovery vehicle is dispatched to the traffic incident. The driver of the broken down vehicle is instructed via radio or public announcement to remain in their vehicle pending recovery. Traffic in the tunnel should be able to negotiate the stranded vehicle without causing serious congestion behind.

Road Traffic Accidents (RTA)

A minor RTA is managed in the same way as a breakdown, however in this instance two or more recovery vehicles may need to be dispatched to deal with the stricken vehicles. In the event of a serious accident where debris blocks the tunnel and traffic backs up behind the incident, a recovery vehicle from the opposite end of the tunnel can use the vehicle cross over outside the portal or vehicular cross passages within the tunnel to enter the incident tunnel. The emergency services enter in a similar manner. Variable Message Signs (VMS) and lane closure indicators are activated by the TCC to warn tunnel users about an incident and if necessary, the incident tunnel is closed and alternative traffic management plans are implemented. These could include the introduction of a temporary contra-flow system in the non-incident bore or complete diversion to an alternative route.

Fire

Access for the emergency services is provided in number of ways depending on the circumstances. They can drive down the affected bore directly to the incident if there is no traffic blocking the route. Alternatively, if the route is blocked, the non-affected bore can be closed to traffic and the emergency services can use the crossovers at each portal to access the non-affected bore. From there access to the incident is via the nearest pedestrian cross passage on foot or they can use the nearest vehicle cross passage to drive directly to the incident bringing all the necessary heavy equipment with them. If vehicular access is not possible or preferable, emergency access points are located in the ventilation shafts on each shoreline, which provide access on foot via stairs and lifts.

B4.2 Possible Evacuation Procedures

Evacuation of tunnel users in an emergency would be carried out via the pedestrian cross passages and the non-affected bore. Pedestrian cross passages are provided at 200 metre intervals. Emergency walkways are raised above the carriageway by only 75 millimetres so that a wheelchair can easily negotiate the kerb and continue into the cross passage. Once through to the non-affected bore, the traffic may still be running unaffected by the incident in the other tube. Consequently full width offside walkways are provided so that people can safely continue along the non-affected tunnel away from the incident and prevent a back up of people through the cross passages.

Emergency exits would be located in the ventilation shafts on each shoreline. Stairs and lifts would be provided so that a suitable escape route is available for disabled people.

This procedure is the same for all proposed tunnel construction techniques and cross sections. The only difference is that the immersed tube tunnel has a central service cell in lieu of the cross passages. However, these are accessed in the same way via fire proof doors and the same procedure applies. Similarly, the C&C tunnel has doors through the central walls between the two traffic spaces.

Requirements for the ventilation system are such that ventilation would be provided in the cross passages and that positive pressure or other means of excluding smoke from the cross passages and non-affected bore would be provided. The ventilation system also must provide a means of extracting smoke in the event of a fire, so movement of smoke and fire gases in the tunnel near the incident should be minimised or eliminated by the ventilation system allowing clear unrestricted means of escape for users in the vicinity of the incident.

B4.3 Possible Intervention Procedures

Access for the emergency services would be provided in number of ways depending on the circumstances.

The first scenario is they can drive down the affected bore directly to the incident if there is no traffic blocking the route. Alternatively, if the traffic is stopped behind the incident and the route is blocked, the non-affected bore can be closed to traffic and the emergency services can use the crossovers at each portal to access the non-affected bore. From here the emergency vehicle can stop at the nearest pedestrian cross passage (at 200 metre intervals) to the incident and proceed on foot or they can use the nearest vehicle cross passage (at 1,500 metre intervals) to drive directly to the incident bringing all the necessary heavy equipment with them.

If vehicular access is not possible or preferable, emergency access points are located in the ventilation shafts on each shoreline, which provide access on foot via stairs and lifts. The emergency personnel can then continue on foot down the affected bore directly to the incident. Alternatively they can proceed down the non-affected bore and access the incident via the nearest pedestrian cross passage. Initially the traffic may still be running in the non-affected bore, so full width walkways are provided on both sides of the carriageway. They are raised above the carriageway by only 75 millimetres so that a wheeled trolley bed can easily negotiate the kerb and continue into the cross passage.

Again this procedure is the same for all proposed tunnel construction methods and cross sections. Figure B6 shows a schematic of the possible emergency evacuation and intervention procedures.

Requirements for the ventilation system are such that ventilation would be provided in the cross passages, and that positive pressure or other means of excluding smoke from the cross passages and non-affected bore would be provided. The ventilation system also must provide a means of extracting smoke in the event of a fire, so movement of smoke and fire gases in the tunnel near the incident should be minimised or eliminated by the ventilation system allowing clear unrestricted access for the emergency services.

B4.4 Hazardous Goods

The passage of hazardous goods through the tunnel is subject to restrictions as outlined in the British Toll Tunnels Dangerous Traffic List of Restrictions booklet which is currently in its thirteenth edition. The basis of this list is the restructured ADR (2005 European Agreement concerning the international Carriage of Dangerous Goods by Road) as amended by the Report of the Committee of Experts meeting in December 2004.

The booklet includes a list of restrictions in which the materials are arranged in ascending U.N. Number order. The restrictions, which include prohibition where appropriate, are shown against each entry. An alphabetical index, which includes chemical synonyms, and which enables the U.N. Number of a material to be identified, follows the list of restrictions. The classes of dangerous goods according to ADR are the following:

Class 1: Explosive substances and articles;

Class 2: Gases, compressed, liquefied or refrigerant;

Class 3: Flammable liquids;

Class 4.1: Flammable solids, self-reactive substances and solid desensitised explosives;

Class 4.2: Substances liable to spontaneous combustion;

Class 4.3: Substances which in contact with water emit flammable gases;

Class 5.1: Oxidising substances;

Class 5.2: Organic peroxides;

Class 6.1: Toxic substances;

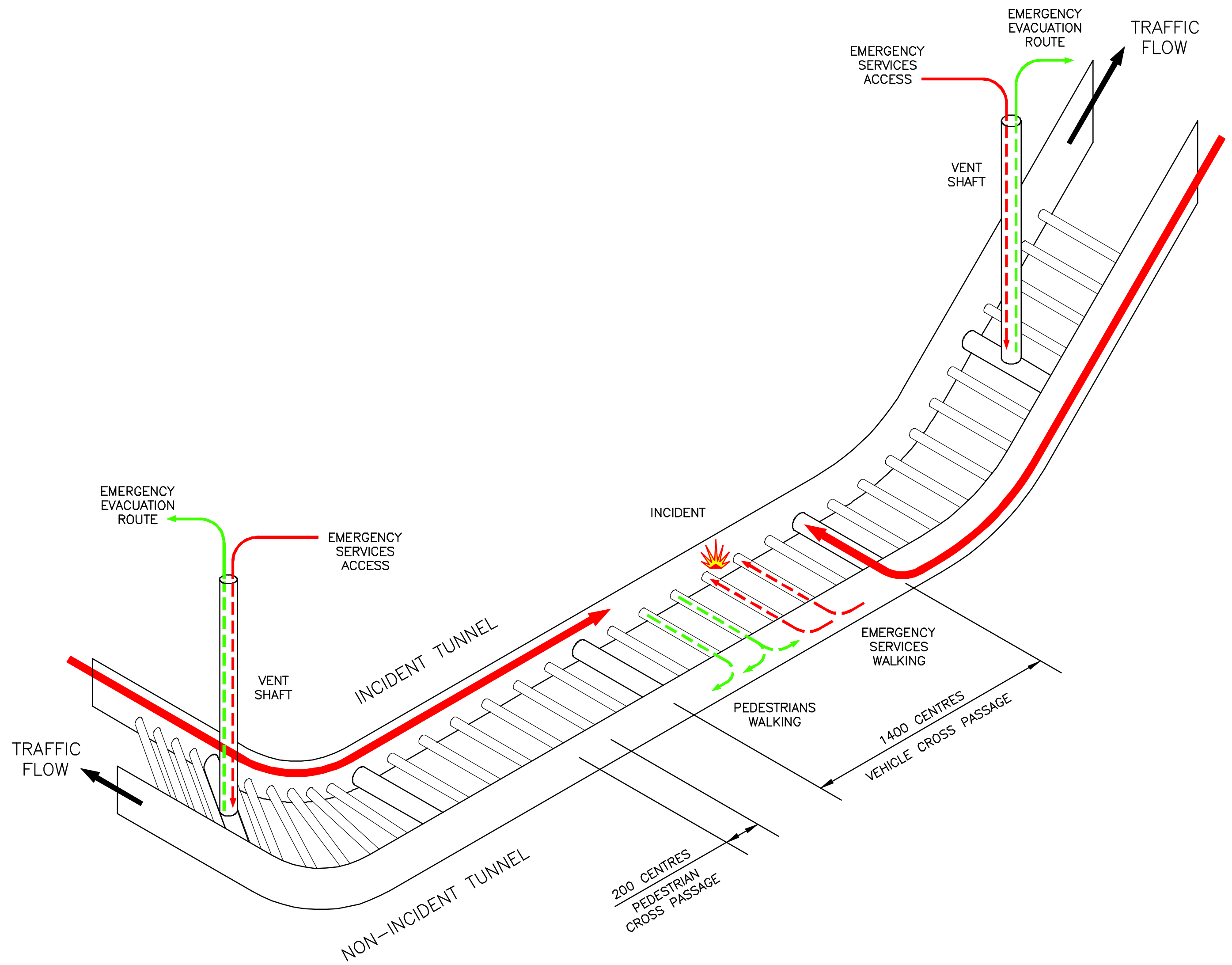
Class 6.2: Infectious substances;

Class 7: Radioactive material;

Class 8: Corrosive substances; and

Class 9: Miscellaneous dangerous substances and articles.

Larger loads and tankers carrying hazardous goods are generally prohibited, but it depends on the substance. Some may be permitted under escort. To gain approval for carriage of hazardous good through the tunnel the consignor of any goods, substances or articles on the list of restrictions, must submit to the Tunnel Manager a written declaration as to the nature and quantity of such goods, and, similarly for an empty petrol or other tanker, a declaration is required as to the nature of the substance last carried if it has not been cleaned since that loaded journey. Permission may be granted for passage through the tunnel at a prescribed off peak time when the tunnel can be closed to the public following notification to the public of the temporary tunnel closure.



INTERVENTION AND EVACUATION SCHEMATIC

FIGURE B6

B5 COST AND PROGRAMME ESTIMATION

B5.1 Construction Costs

Introduction

The construction cost estimates for the three different tunnel options have been determined by carrying out a 'bottom-up' estimate for one of the options. This process was used to calculate an all inclusive cost per unit metre length for each of the tunnelling techniques employed. This unit cost was then used in the estimation of costs for the other two options.

This report looks at the construction costs of the tunnels from portal to portal and does not cover the network connections, approach ramps or the cost of any possible toll plaza.

A summary table of costs for each of the options is contained in Section 5.10 of Volume1: Main Report. In addition, the applications of optimism bias uplift, design and client costs are also contained in the cost estimates in the Main Report.

BOTTOM UP COST APPROACH

The cost estimate for Corridor C Tunnel was derived by using a detailed 'bottom up' costing approach. The bottom up approach defines the different construction elements and calculates the associated costs separately before adding them together to form the overall project cost estimate. The basis for developing the bottom up cost estimate for Corridor C Tunnel has been by deriving the components and quantities involved in the construction of the tunnel from the outline design carried out as part of this study. Rates for site overheads, plant, workmanship and materials have been taken from a range of different underlying cost databases. To ensure the robustness of the estimates the rates have been benchmarked with industry standards and project experience elsewhere. In deriving the rates for each component of work for Corridor C Tunnel, the following assumptions have been made:

<u>TBM Tunnel:</u>

Two 13 metres outer diameter EPB TBMs launched from the same shaft on the southern side of the Forth.

Staggered launch by approximately three months. Average drive rate of 31.3 metres per week.

60 metre diameter launch and reception shafts, approximately 70 metres deep, constructed in two levels by secant pile method. Initial back-shunt by roadheader prior to assembly of TBM.

Precast concrete segmental ring lining 500 millimetres thick, fully bolted with ethylene propylene diene monomer (EPDM) rubber gaskets manufactured and delivered from off-site.

Sprayed Fire Lining 50 millimetres thick.

In situ concrete haunches and road deck supports and precast concrete suspended road deck slab 500 millimetres thick.

100 millimetres thick road surfacing consisting of 65 millimetres binding course and 35 millimetres wearing course.

Construction of cross passages under the Forth by pre-treating (grouting) blocks of ground at 200 metre intervals from a jack-up barge. Pre-treated blocks to be extended at intervals to allow access to the face of the TBM for routine maintenance and adjustments to cutting head to suit varying geological conditions. Further treatment of ground as required ahead of excavation of cross passages through mainline tunnel lining. Excavation rate of 3.5 metres per day assumed.

Two vehicle cross passages assumed at shaft locations for ease of construction. This means that only two are required under the Forth and one on the southern approach tunnel.

Removal of unavoidable dolerite along the alignment carried out from the surface in a caisson or cofferdam. Dolerite mined within cofferdam and tunnel constructed allowing TBM to pass through.

<u>SCL Tunnel:</u>

Four 60 tonne (minimum) roadheaders excavating from the portals towards the shafts. Advance rate of approximately 3.5 metres per day.

Primary support to consist of 300 millimetres thick fibre reinforced shotcrete. An allowance has been made for forepoles, steel ribs and rock dowels/bolts as required near portals, cross passages and poor ground conditions. On-site batching plant for supply of shotcrete.

Waterproof membrane assumed over full area of walls and roof.

Permanent support consists of 600 millimetres thick cast in situ reinforced concrete lining. Four steel CIFA-type travelling forms assumed with pre-fabricated reinforcing cages for the mainline tunnel.

Sprayed Fire Lining 50 millimetres thick.

In situ concrete base slab/road deck 500 millimetres thick.

100 millimetres thick road surfacing consisting of 65 millimetres binding course and 35 millimetres wearing course.

Approximately 5 metres squared trench excavation and construction of reinforced concrete box under the road deck slab for fresh air supply.

Pre-grouting of mine workings from the surface to stabilise ground.

Cut and Cover Tunnel:

Walls constructed with contiguous piles and temporary support by waler beams and anchors/struts.

In situ reinforced concrete base slab/road deck.

Precast concrete roof.

Sprayed Fire Lining 50 millimetres thick.

100 millimetres thick road surfacing consisting of 65 millimetres binding course and 35 millimetres wearing course.

Ventilation:

Fully transverse ventilation system.

Fresh air supply and exhaust/smoke extraction ducts assumed for full length of tunnel.

Air exchange at ventilation stations situated on either bank of the Forth.

No allowance for filtering the exhausted emissions has been included.

Removal of spoil:

Extraction of spoil from both TBM tunnels via the southern shaft. All spoil disposed off site to within an approximate 20 mile radius of the site by road.

Cost Estimates for Corridor D and E Tunnels

The costs for the tunnels on Corridors D and E have been calculated from using the costs derived from the 'bottom-up' estimate for Corridor C Tunnel. The data from Corridor C was used to obtain an all inclusive cost per unit length for each type of tunnelling technique which was then applied to the other corridors to develop the overall costs for each option.

Costs for Corridor C Tunnel were broken into items that are specific to each tunnelling technique and general items that are required regardless of the technique involved. Costs for specific items were divided by the length of the respective tunnelling technique involved, and costs for general items were divided by the whole length of the tunnel to obtain a cost per unit length for each item. An all inclusive cost per unit length for each type of tunnelling technique was calculated by combining the unit rates for all the different items.

The following is a non-exhaustive list of the specific items:

- Procurement of Plant;
- Excavation and line;
- Removal of spoil;
- Civils fit out;
- M&E fit out; and
- Cross passages.

Below is a list of the general items:

- Ventilation Shafts and stacks;
- Ongoing site overheads; and
- Mobilisation costs.

It is noted that the unit cost for the immersed tube tunnel in Corridor E was derived independently from the cost estimate of Corridor C. For this section of the tunnel the unit costs have been derived from the out-turn costs from a database of other major comparable projects in the UK and abroad.

To ensure that out-turn cost for each immersed tube project was consistent, the costs were indexed up to a common base date (fourth quarter 2006) and adjusted by a country factor to suit the UK context. A weighted mean of the unit costs in the database was then adopted.

Also, certain additional costs items have been added to each corridor where appropriate. These costs, whilst also included in Corridor C, were added separately to reflect specific risks and irregularities associated with each individual corridor.

Below is a list of extra cost items:

- Ground treatment associated with the technically challenging construction of cross passages under the Forth;
- Old mine workings in the vicinity has meant that ground treatment along the southern banks of the Firth for Corridor C and E has been allowed for;
- Removal of unavoidable dolerite in the path of the TBM by intervening from the surface to provide a dry area to drill and blast and then excavate; and
- Unforeseen obstructions at the face of the TBM.

Risk Analysis

At this stage of the project's conceptual phase, a full detailed risk analysis has yet to be carried out. Due to the limited geotechnical information presently available, it is anticipated that costs associated with tunnelling through different rock types could vary considerably following the results of a more detailed site investigation. Other areas of technical complexity with large unknowns, such as the lowering of immersed tube sections into an area with strong tidal and river flows, are difficult to analyse without first carrying out detailed local flow studies. Risks associated with these uncertainties are likely to have considerable cost implications should any of these tunnel options be chosen for further development.

Optimism Bias Uplift

Optimism bias is defined by British Department of Transport as "a systematic empirical based adjustment made to project cost, benefits and duration to counteract traditional over optimism of appraisers and ensure that risks of cost overruns is below the certain predefined levels."

In line with the current optimism bias standards for projects for this kind in the UK, an optimism bias value of 66 per cent has been assumed.

Additional Cost Factors and Assumptions

The focus of this report is limited to the construction costs for the tunnels only. Additional cost factors must be applied on top of construction costs to provide an estimate of the complete cost of the project. These costs are covered in the project cost estimates in Volume1: Main Report.

The following cost factors are not considered in this report:

- Client costs, assumed to be 5% of construction costs;
- Preparation & Design costs, assumed to 12% of construction costs;
- Contractor insurance, assumed to be 2.5% of construction costs;
- Contractor profit, assumed to be 4% of construction costs;
- Spend profiles;
- Network connection costs;
- Land costs;
- Optimism Bias Uplift, assumed to be 66%; and
- Ground investigation cost.

B5.2 Operation and Maintenance Costs

Introduction

A cost estimate of the operation and maintenance costs has been carried out by reviewing reported costs for the existing Forth crossing as well as a review of power supply requirements for tunnel services such as lighting and ventilation from other similar tunnelling projects in the UK and abroad.

Operations

Whilst each of the proposed tunnels vary in length and alignment, the operational costs associated with running administration duties, staff maintenance, traffic operations, and toll collection (if required) would broadly be consistent between all three corridor options and have been assumed to be the same for this report.

A review of the recent financial information reported by the Forth Estuary Transportation Authority, (FETA) has provided the basis for the expenditure for operational costs. An additional sum was added to account for the operation of a control room 24 hours a day seven days a week.

Maintenance

There are a number of installations in the tunnels that have to be periodically replaced. These include pumps, drainage pipes, fans, electrical installations and water and frost linings. The annual costs for these items are would vary from year to year but would even out over an assumed whole life cost of 60 years. The improving and replacing of some installations, in particular ventilation shaft fans, can be quite expensive.

Power Supply

Long tunnels such as these, designed with a fully transverse or semi transverse ventilation system provide a steady supply of fresh air into the tunnel. A constant power supply is therefore required to turn the fans. These costs, along with lighting costs, can be a considerable share of the overall operation and maintenance burden.

Table B6 summarises the approach taken in calculating the operation and maintenance costs.

Table B6 – Operation and Maintenance Cost Approach Summary

Categories	Description	Cost Approach	Unit Cost	Unit
Operational	Administration, Traffic Operations, Toll Collection.	Based on financial reporting from existing forth crossing.	N/A	N/A
Maintenance	Dewatering, Road Surfacing, Periodic Replacement of M&E.	Unit cost developed from similar projects and Highway Agency guidelines.	Unit cost per length of tunnel	£ per metre
Power Supply	Power supply to key services; ventilation and lighting.	Unit cost developed from similar projects.	Unit cost per length of tunnel	£ per metre

B5.3 Programme

An example construction programme for Corridor C Tunnel is shown in Figure B7. The programme does not include the planning and design stages.

A number of general assumptions were required to enable the construction programme to be drafted. These are listed below:

The geotechnical conditions encountered are as currently envisaged based on the limited data currently available. Therefore a mined SCL tunnel has been assumed from the portals to the ventilation shafts near the shoreline with a bored TBM tunnel under the Forth;

- Both TBM tunnel tubes excavated northwards with two 13 metres outer diameter EPB TBMs launched from the same shaft on the southern side of the Forth;

- Extraction of spoil from both TBM tunnels via the shaft near the southern shoreline. All spoil disposed off site to within an approximate 20 mile radius of the site by road; and

- The programme assumes that construction commences from three of the four work sites simultaneously.

Procurement and delivery of the two TBMs is anticipated to take 12 months. During this time, site establishment and all enabling works commence. Construction of the southern TBM launch shaft and excavation of the cuttings at the portals follows to enable the tunnelling operations to get underway without delay.

The pre-treatment of blocks of ground under the Forth by drilling and grouting from a jack-up barge for construction of the cross passages also commences at the beginning of the programme. This enables the process to stay ahead of the TBM drive. It is not, however, on the critical path, so any delays that may result from environmental or ecological mitigation would not adversely affect the overall programme.

The first tunnelling exercise envisaged is a short mined back-shunt in the southern shaft to allow assembly of the TBM back-up train upon delivery. The roadheaders are then extracted and launched from the portals where excavation proceeds down the four approach tunnels towards the shafts. An average advance rate of 3.33 metres per day has been assumed giving a total drive time of 26 months on the northern side and 15 months on the southern side.

Construction of the northern shaft commences after completion of the southern shaft. TBM excavation commences in the first bore after three months of assembly and launching. The excavation rate has been assumed at an average of 31.3 metres per week giving a total drive time of 32 months. Excavation of the second bore follows approximately three months after the first so the assembly crew can begin on the second machine immediately after launch of the first.

Construction of the cross passages can commence in the SCL tunnels while excavation of the mainline is still underway, while it has been assumed that excavation of the cross passages in the TBM tunnel would not commence until after completion of the mainline excavation.

Fit out of the civil works in the SCL tunnel commences after completion of the cross passages. Installation of the mechanical and electrical components can be carried out simultaneously behind the civils fit-out.

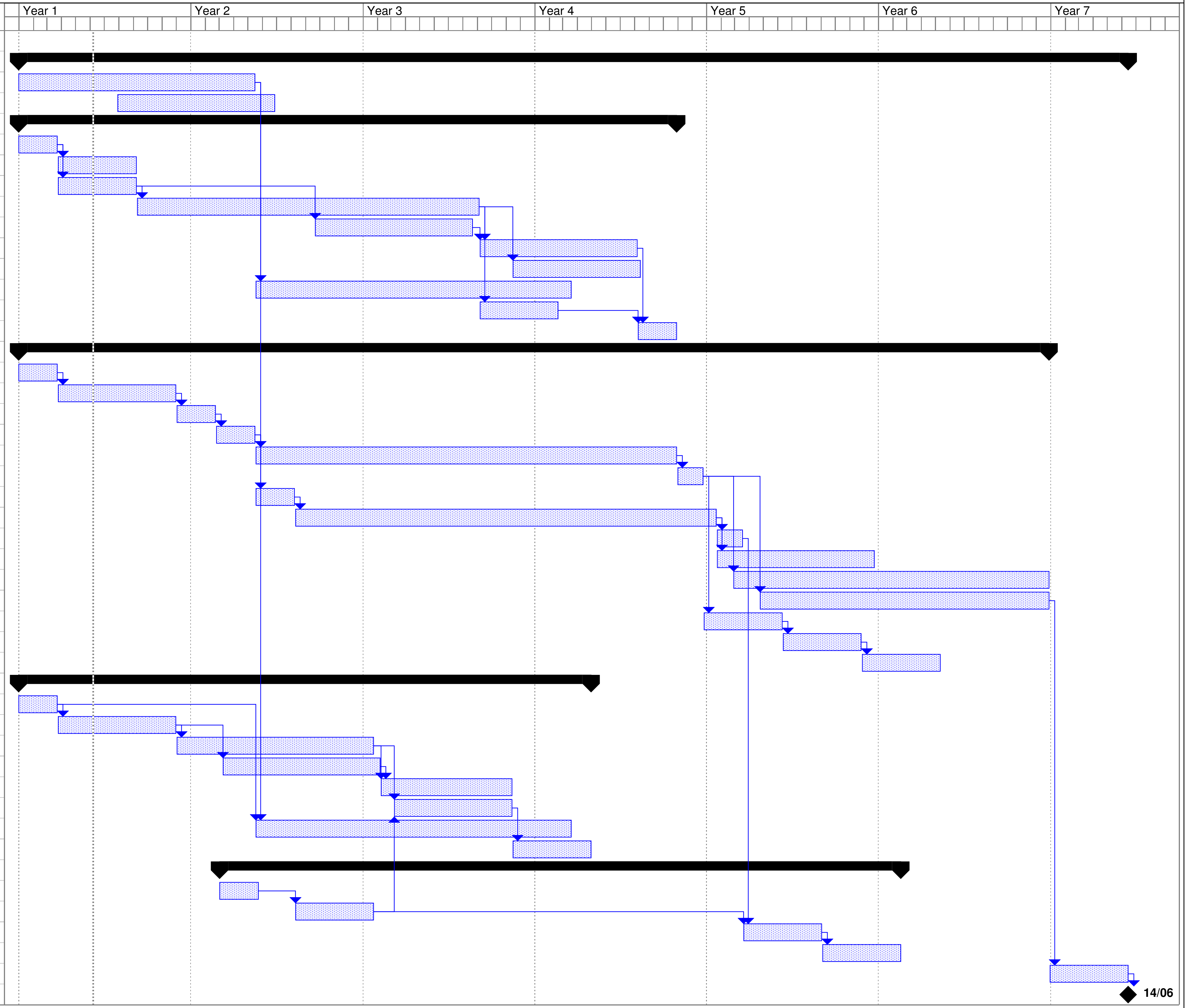
The programme assumes that fit out of the SCL tunnels is substantially complete before fit out begins in the TBM tunnels. Delivery of materials and equipment can now be re-directed through the portals and the SCL tunnels. This allows access from the shafts to be closed off and construction of the vehicle cross passages and ventilation stacks can proceed in the shafts.

Commissioning and testing follows substantial completion of construction and is the last item before hand-over and opening to traffic.

FIGURE B7

Forth Replacement Crossing Study
Example: Tunnel Option C
Construction Programme

ID	Task Name	Duration
1		
2	**Construction**	**1685 days**
3	Enabling works and utility diversions	72 wks
4	Ground treatment for x-passages under estuary	12 mons
5	**Southern Portal Site (Mined Section)**	**1000 days**
6	Site mobilsation	12 wks
7	Grouting in mine workings	6 mons
8	Excavation for cutting at portal	6 mons
9	Roadheader mining and lining	26 mons
10	Cross passages	12 mons
11	Tunnel fit-out	12 mons
12	M&E	9.75 mons
13	Junctions/ Roads/ Bridges	24 mons
14	Toll plaza	6 mons
15	Aproach ramp	3 mons
16	**South Ventilation Shaft Site (TBM Section)**	**1565 days**
17	Site mobilisation	12 wks
18	Shaft sinking	9 mons
19	Launch chamber for TBMs	3 mons
20	TBM launch/ essembly (bore 1)	3 mons
21	TBM excavation and linining (bore 1)	32 mons
22	TBM disessembly	2 mons
23	TBM launch/ essembly (bore 2)	3 mons
24	TBM excavation and linining (bore 2)	32 mons
25	TBM disessembly	2 mons
26	Cross pasages	12 mons
27	Fit-out of TBM section	24 mons
28	M&E of TBM section	22 mons
29	Ventilation stack construction	6 mons
30	Ventilation Stack M&E	6 mons
31	Permanent site access	6 mons
32	**North Portal Site (C&C, Mined Section)**	**870 days**
33	Site mobilisation	12 wks
34	Excavation for cutting at portal	9 mons
35	Roadheader mining and lining	15 mons
36	Cross passages	12 mons
37	Tunnel fit-out	10 mons
38	M&E	9 mons
39	Junctions/ Roads/ Bridges North	24 mons
40	Approach Ramp and Cut & Cover roof	6 mons
41	**North Ventilation Shaft Site**	**1035 days**
42	Site mobilisation	12 wks
43	Shaft sinking	6 mons
44	Ventilation stack construction	6 mons
45	Ventilation stack M&E	6 mons
46	Commisioning, Testing and Snagging	6 mons
47	Tunnel Opens	0 wks



Project: Forth Crossing Tunnel Progra
Date: Thu 07/06/07

Task	Progress	Summary	External Tasks	Deadline
Split	Milestone	Project Summary	External Milestone	

B6 TUNNELLING TECHNIQUES

B6.1 Bored Tunnels with Tunnel Boring Machines

General

A TBM is a relatively commonplace excavation method for the construction of utility, sewer, road and rail tunnels. TBMs come in a variety of sizes and configurations and can deal with ground conditions that range from unconsolidated loose soils to extremely hard rock and very high groundwater pressures. TBMs may be launched from a shaft or from a deep cutting. As they remain below ground the use of TBMs can avoid many of the environmental issues that affect shallow tunnels or surface structures.

TBM excavation relies on rotation of a cutting head against the ground; the tunnel profile created is therefore circular. This means that all elements of the tunnel must fit within the circular profile of the tunnel, unless the tunnel is later enlarged to accommodate the required changes in tunnel diameter or shape. The diameter of the bore is critical due to the high costs associated with procurement of the larger diameter TBMs. It is not uncommon to restrict the widths of carriageways and hard shoulders in order to minimise the diameter of the TBM required. Other factors include restricted radii on horizontal curves due to the minimum required stopping sight distances.

The size of the TBM anticipated for use on the Forth crossing would be in the region of 13 metre diameter which is approaching the largest diameter that has been used before.

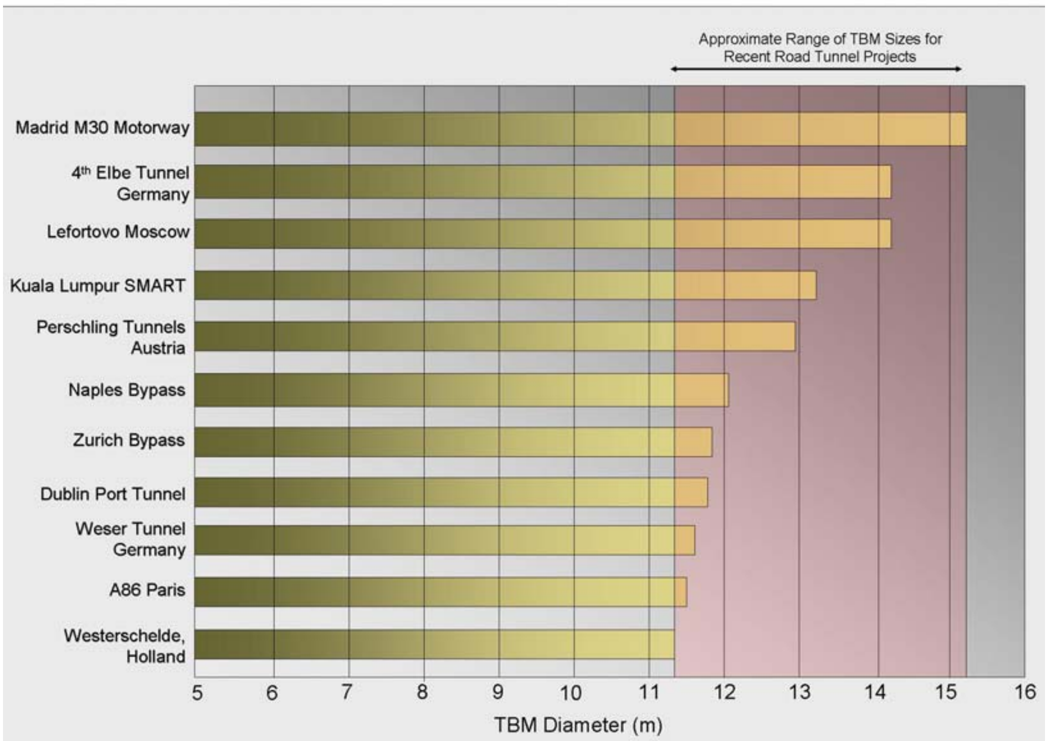


Figure B8 – Range of TBM Sizes for Recent Major Road Scheme

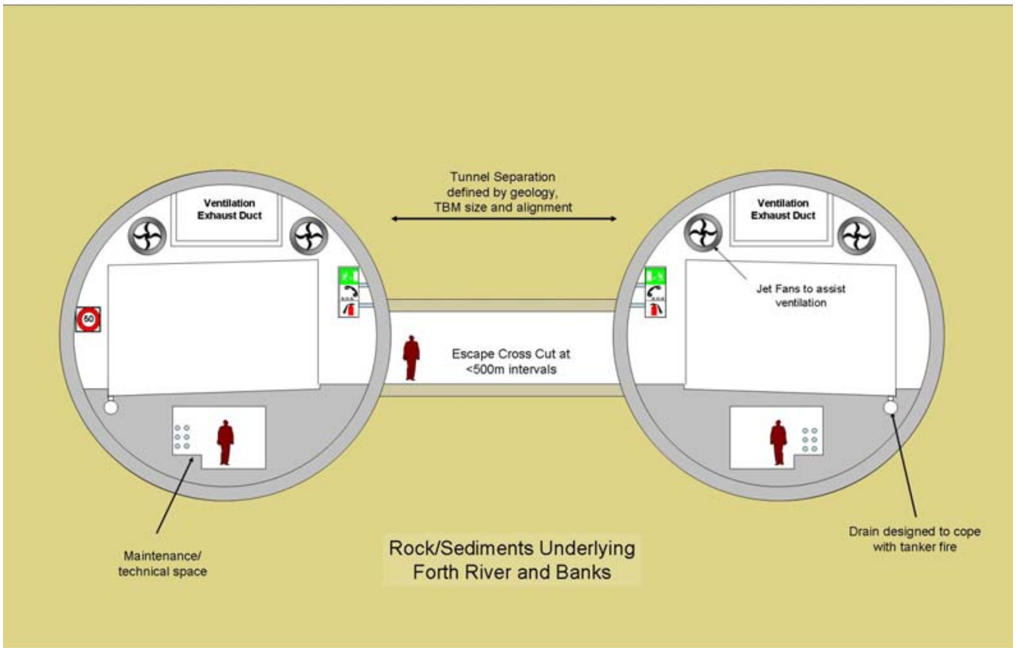


Figure B9 – Generalised Schematic of Typical Bored TBM Tunnel

Construction Methodology

There are three main types of TBM depending on the ground conditions:

Open Face

This method of excavation is similar to that of a mined Sprayed Concrete Lining tunnel, where the excavated face is largely exposed and unsupported during excavation. A roadheader or backhoe is used to excavate the face as the TBM advances. Precast segmental lining is installed behind the face in the usual manner. This method is suitable for stable cohesive materials such as stiff clay and soft rock.

Full Face

There is a full face rotary cutting head which provides limited support to the excavated face, usually by limiting the rate that spoil is passed through the cutting head. This method is limited to cohesive soils.

Closed Face

The excavated face is contained and supported all at times. This is achieved by Earth Pressure Balance (EPB) machines which pump in pressurised fluids that modify or homogenise the excavated material to allow controlled and consistent face pressure to be applied. This significantly reduces the amount of face loss and surface settlement as a result. However, it is the most expensive method in terms of procurement of the TBM and operating costs. This method is suitable for cohesionless soils and where high water pressures are expected.

A TBM comprises four elements:

Cutting Head

Typical TBMs cut the strata using a circular cutting head armed with cutters placed on a single head, on spokes or (for the larger TBMs) two concentric rotating heads. Cutters and their configuration are designed for the different ground types expected. These are generally chisels and picks for soft rocks and soils and rolling cutting discs for hard rock, or a combination of both where mixed ground is anticipated.

The configuration of the cutting head also manipulates the excavated material onto the waste handling system that runs inside the TBM.

Drive Section

The drive section houses the motors that provide the rotational drive for the TBM and power a series of hydraulic rams in soils and/or grippers in rock to provide thrust. The rams bear against the lining that has been erected behind and the grippers bear directly against the walls of the excavated tunnel. The TBM cutting action requires a thrust to be placed on the cutting head. This thrust serves three purposes:

- To increase cutting action of the cutters by forcing them into the ground;
- To move the TBM forward through the ground during the cutting cycle; and
- To provide a face pressure to support the material in front of the TBM to minimise settlement.

Tail Shield

For tunnels excavated entirely in competent and dry rock, no structural lining may be required behind the boring machine, and therefore no tail shield is required. However, for the range of ground conditions and high water pressures anticipated in the Forth area, a watertight lining would have to be placed behind the TBM to support the ground and to prevent groundwater ingress. This would be erected within a tail shield directly behind the TBM.

Segmental linings are the most commonly applied lining in the ground conditions anticipated. These are rectangular or trapezoidal segments that, when bolted together form a circular lining. Waterproofing is achieved by using gaskets and hydrophilic strips between segments. The lining is grouted in place to maintain its shape and provides an additional means of enhancing waterproofing.

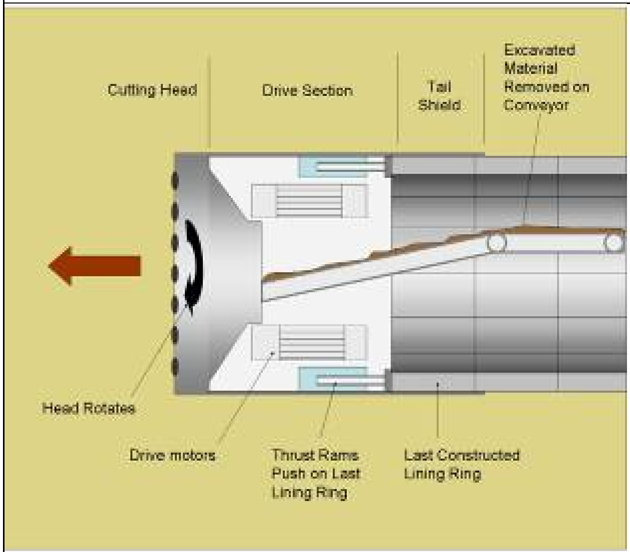
Back-up or Trailing Gear

The supply of lining and grouting materials and the efficient removal of waste from the TBM is critical to the efficiency of the tunnelling process. TBMs generally pull trailing apparatus that allows simultaneous extraction of excavated material and delivery of lining segments and grout. This usually consists of a conveyor belt running on top of a gantry system. Transportation of the waste and materials can use small trains or long conveyor belts, depending on the length and diameter of tunnel, the type of waste and the contractor’s equipment.

The back-up generally carries additional items such as grout pumps, soil conditioning chemicals and their pump systems, fire-fighting equipment, ventilation, environmental monitoring and emergency systems. On large machines they include drivers cabins, canteen and ablution facilities. The back-up gear is usually the longest element of the TBM and can be up to 250 metres in length.

TBM tunnelling involves a two stage cycle to create the tunnel bore and this process is illustrated in Figures B10 and B11:

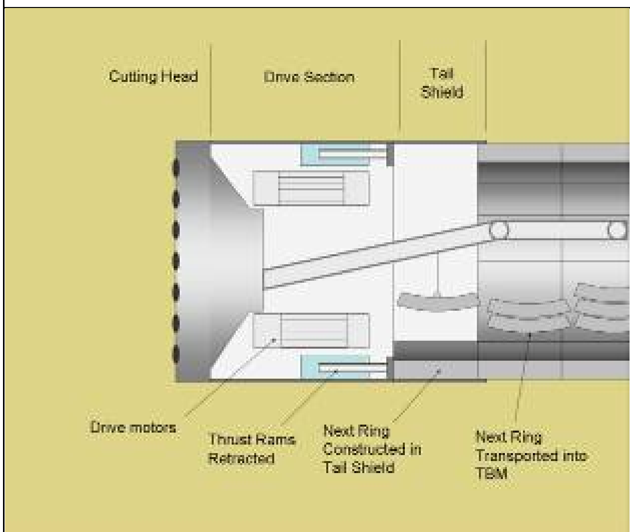
Stage 1 - Excavation Advance



- The cutting head is rotated against the ground to commence cutting.
- Thrust is applied by the rams or side gripper pads in the Drive Section to assist cutting and maintain face pressure.
- Cutting and advance continues until enough space is created in the Tail Shield to construct the next lining ring.
- The gap between the ground and the previous lining ring is grouted as it leaves the tail shield.

Figure B10 – TBM Excavation Sequence: Stage 1

Stage 2 – Lining Erection



- The thrust rams are withdrawn into the Drive Section leaving clear space for the erection of the lining.
- Each segment forming the lining is manoeuvred into position and bolted together to form a completed lining ring.
- The thrust rams are then re-engaged to commence the next excavation cycle.

Figure B11 – TBM Excavation Sequence: Stage 2

Geotechnical Conditions and Constraints

Ground conditions are critical for all tunnels, but they place particular requirements on TBMs. Generally the larger the TBM, the narrower the range of ground conditions the machine can cope with, and the softer the ground needs to be. This is due to increased power requirements to turn the cutting head in harder ground conditions. A Forth tunnel alignment could be expected to encounter the following:

- "Coal measures" comprising limestone, sandstone, shales and coal seams;
- Alluvial silts, sands and gravels in the glacial channel under the Firth; and
- Dolerite dykes closer to Beamer Rock and the existing bridges.

Current TBMs of the size ranges required have been configured for projects that include coal measures and alluvial deposits. However, TBMs are not commonly used for hard rock like dolerite, so if large sections of dolerite were on the alignment it is anticipated that they would be excavated from the surface by constructing a caisson or cofferdam and mining through the dolerite by drill and blast or other suitable means.

The TBM that would be used for the Forth crossing would have to be a EPB machine due to the expected high water pressures and granular nature of the glacial and alluvial deposits under the Firth. This is the most expensive type of TBM. It is also possible that unexpected obstructions may be encountered in the glacial and alluvial deposits. These may include large boulders or trees that have remained in the Firth sediments. A large diameter EPB TBM designed for soft sediments is unlikely to be able to excavate through these and intervention at the cutting face may be required. Given the hydrostatic pressure, this would have to be carried out under compressed air conditions. This would require decompression facilities and would cause a considerable delay in the construction programme.

Environmental Impacts

The banks of the Forth are almost exclusively designated as Special Protection Area (SPA), Site of Special Scientific Interest (SSSI) or RAMSAR. Tunnelling using a TBM would not directly affect these areas or other designated sites along the banks. However, the excavation of a large reception and launching shaft on the shores would have an impact. The location of any launch shafts should be carefully chosen to minimise the impact. Alternatively the TBM may be launched from the portal approach ramps. The TBM can start and finish tunnelling with approximately one diameter of cover, although this can be reduced under certain circumstances. A long approach ramp or large shaft is therefore generally required at either end of the TBM tunnel.

Removal of significant amounts of excavated spoil may impact on the area surrounding the portals or launch shafts. Spoil may be stockpiled temporarily on site depending on the available space. It may be extracted at either the portal or shaft locations or both, depending on the construction methodology. In any case, it is inevitable that the spoil would need to be transported off-site. A suitable disposal area would need to be found in the locality to limit the transport distance. Considering a TBM of 13 metres diameter, and an average tunnel length for the Forth crossing of 7.5 kilometres, this equates to approximately one million cubic metres of spoil to be disposed at each side of the crossing assuming equal amounts of excavation from both ends. This is equivalent to almost two million tonnes or over 65,000 truck movements at each side if all spoil is removed by road which is the most likely option.

Most of the tunnelling under the Forth would pass through soft river sediments resulting in high water pressures at the cutting face. As previously mentioned, an EPB machine would be required. This process involves pumping in pressurised fluids that modify or homogenise the excavated material to allow controlled and consistent face pressure to be applied. These fluids can be bentonite, foams or polymers all of which need to be separated from the spoil prior to disposal. Failure to separate these fluids correctly would leave the spoil contaminated.

Ventilation and Shaft Access

Due to the overall length of the Forth Crossing tunnel, it is anticipated that a fresh air supply would be needed over the full length of the tunnel. This could be accommodated under the road surface if a fully transverse ventilation system is specified, or in a supply duct suspended from the ceiling in a semi-transverse system. This upper duct is used to extract vehicle exhaust fumes in the fully transverse system. Both systems use this duct for removal of smoke in the event of a fire.

The ventilation shafts and emergency access/egress points would be located on the shores of the Forth. These shafts could form the interface between a mined SCL tunnel and the bored TBM tunnel and could be used as potential launch and reception chambers. The shafts would be constructed from ground level and would large enough so that all equipment could be incorporated within the shaft. Shaft details would have no effect on the cross section of the TBM tunnel.

Flotation

The TBM tunnel under the Forth would be constructed with a minimum of two diameters of cover between the top of the tunnel and the river bed. At this depth, there is enough weight of material on the tunnel to counteract the effects of flotation.

Flooding

It is anticipated that the tunnel under the Forth would pass through soft river sediments resulting in high hydrostatic pressure at the cutting face. An EPB machine would be required. This process involves pumping in pressurised fluids that modify or homogenise the excavated material to allow controlled and consistent face pressure to be applied that is in equilibrium with the external water pressures. Careful monitoring of this process significantly reduces the chances of inundation.

Construction of the cross passages presents a significant challenge in the anticipated conditions under the Forth. These may be done by mining, which does not provide pressure balanced face support. There are several techniques available to enable the passages to be safely excavated, such as ground freezing or excavation under compressed air conditions. However, for safety reasons, the design of the main TBM tunnels may have to include a provision for watertight bulkheads at intervals along the tunnel during construction to prevent complete inundation of the tunnel in the event of an accident.

Breakdown of Machinery

Inevitably, the process of tunnelling using a TBM is heavily dependent on the reliability of the TBM, particularly the components at its cutting head. However, experienced TBM operators would know which parts of the machine are susceptible to failure and which parts need to be routinely replaced due to wear. A comprehensive supply of spare parts should be available and easily accessible to the construction site so that the excavation process is not unduly delayed in the event of a failure.

Approach Ramp Construction

Conventional approach ramps can be used to interface with a TBM portal. The TBM portal generally requires a minimum of one diameter of cover depending on the quality of the overlying material. This means that the approach ramp would be in the region of 20 metres deep. Assuming the topography is reasonably level at the portal location, creating a battered cutting to an excavation as deep as 20 metres is not usually feasible given the space required. Where the excavation is in rock, the sides can be cut steeper or retaining walls constructed so that a vertical cut can be obtained and the land take is minimised. Permanent retaining walls up to 20 metres deep would require anchors that would possibly extend beyond the tunnel or road corridor. Given these considerations, it is common to provide a short cut and cover tunnel from the driven portal to a new daylight portal where the height of the permanent retaining walls required is less significant.

Cross Passages

Construction of cross passages present a significant challenge in TBM tunnels where the ground conditions are soft or high water pressures exist. The TBM continues along the main tunnel as normal but a special lining segment is installed at the cross passage location which acts as a soft eye. The cross passages must be constructed by the mined method as they are too short for even a small TBM. Mining in soft ground presents difficulties as the face of the excavation is unsupported during construction. There are numerous methods of ground improvement available, such as ground freezing, that allow mining to be carried out in such conditions, or compressed air may be used to allow mining to proceed in soft ground with hydrostatic pressure. This is discussed further in Section 6.2.

Rate of Construction

The following graphs illustrate the length and duration of construction of a number of recent TBM tunnelling projects of the similar scope and size:

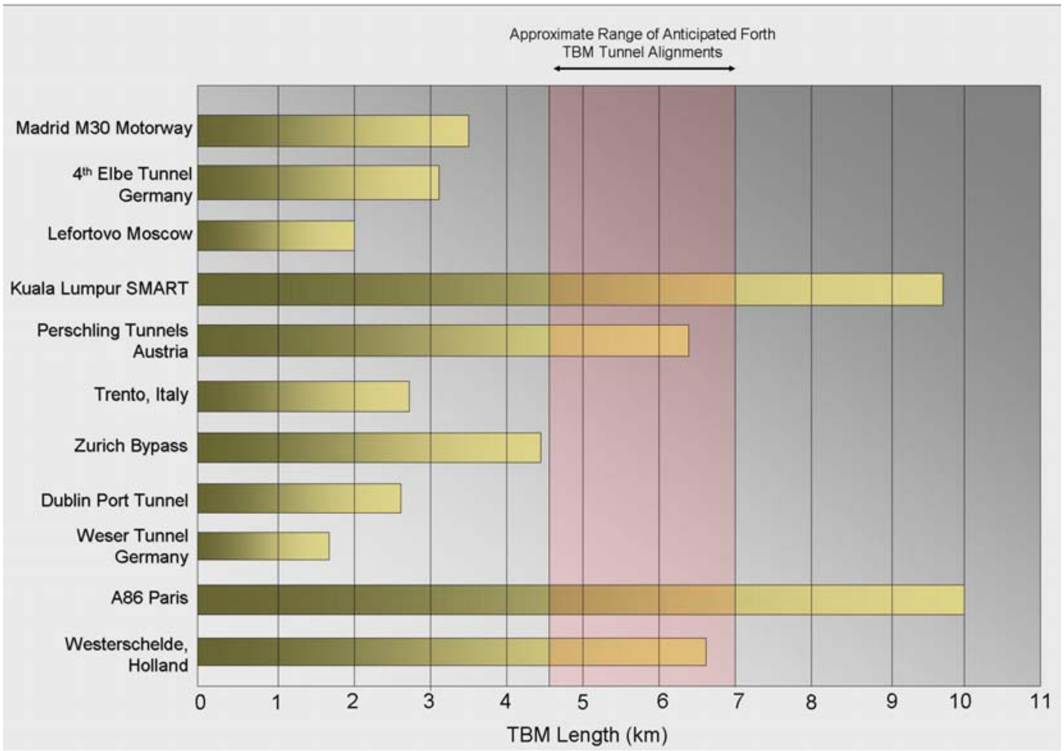


Figure B12 – Approximate Length of TBM Alignments for Comparable Projects in terms of diameter of bore.

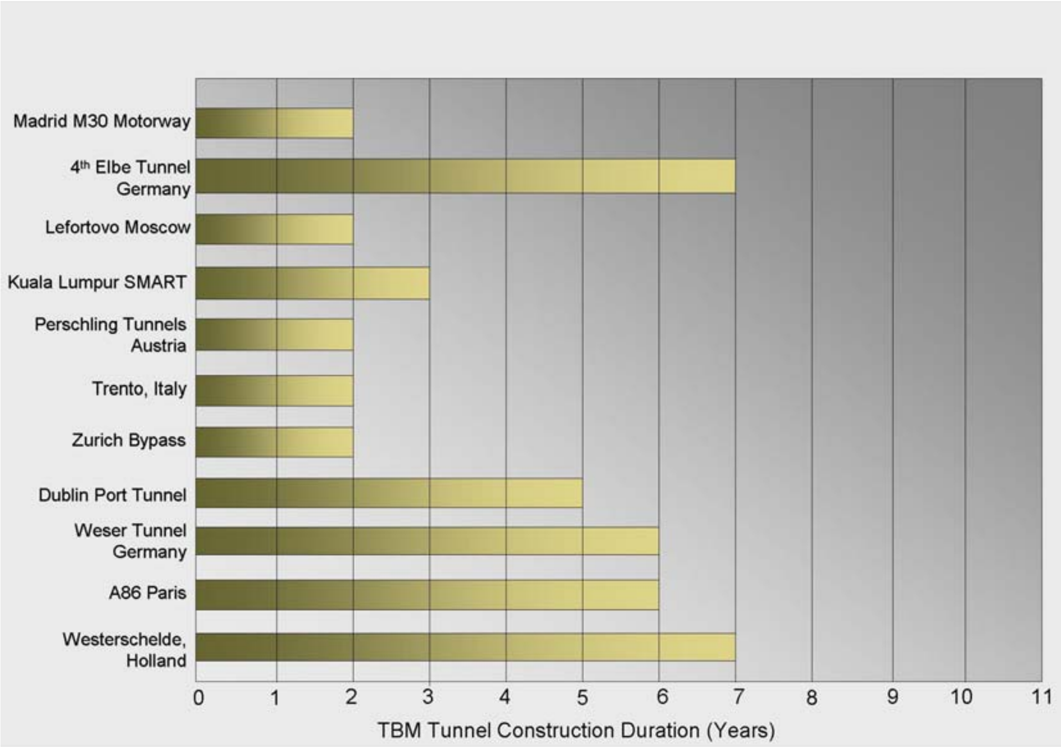


Figure B13 – TBM Construction Durations for Similar Projects

B6.2 Mined Tunnels with Sprayed Concrete Lining (SCL)

General

Many road tunnels have been excavated by mining and using a sprayed concrete lining. This is particularly suited to road tunnel construction as a more rectangular shape is obtained than with a TBM. This is advantageous given that no over excavation is needed and there is no excess space in the excavated cross section leading to cost savings. This method also gives a greater flexibility in terms of shapes and sizes, meaning that the tunnel shape can be tailored and optimised to suit local conditions along the length of the tunnel rather than applying limiting space proofing to the entire tunnel length.

The nature of the technique provides flexibility in regard to the tunnel shape. It makes the provision of enlargements and varying tunnel cross sections viable resulting in economic options for dealing with alignment problems or provision of lay-bys. This is particularly useful in maintaining stopping sight distances at tight curves in the alignment, thus making alignments possible that are impractical using other tunnelling methods. It is also advantageous where other variations in the shape of the tunnel are required, for example safety niches and break down bays can be easily provided, and tunnel intersections and cross passages can be dealt with easier than with bored TBM tunnels.

This method is generally only suited to construction in dry competent rock, and it would be anticipated to be used as approaches to a bored TBM tunnel which would be used under the Forth estuary where glacial and alluvial deposits are expected to be encountered with high hydrostatic pressures.

A generalised schematic of a mined SCL tunnel is shown in Figure B14:

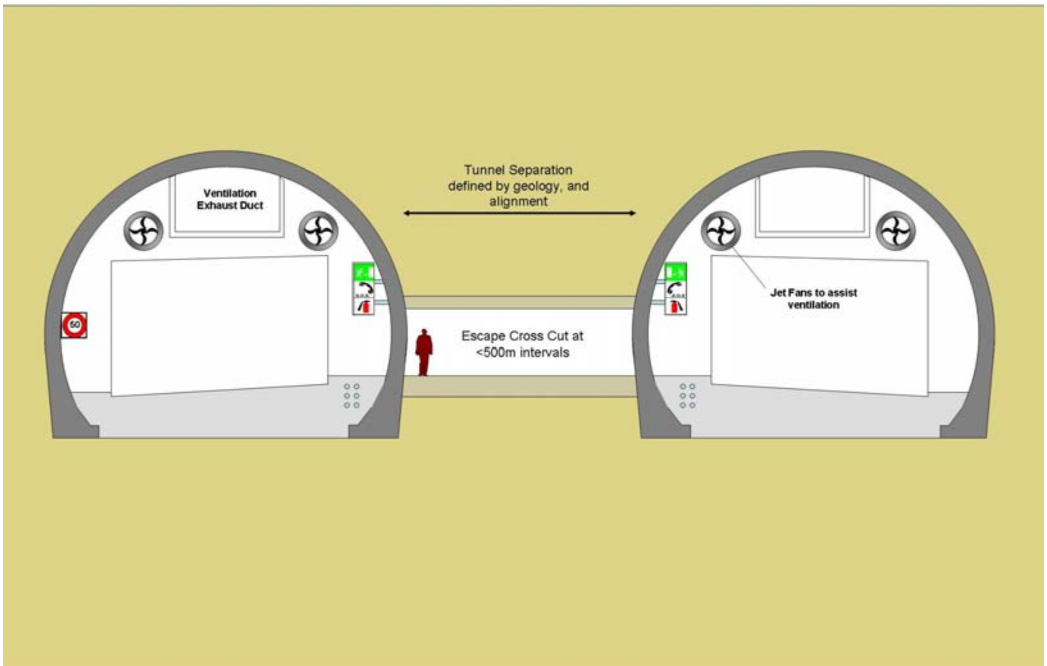


Figure B14 – Generalised Schematic of Typical Mined SCL Tunnel

Construction Methodology

There are a number of key elements to the construction process:

Excavation

The majority of excavation work in sprayed concrete tunnel construction is done using an excavator such as a roadheader or a backhoe. A roadheader has a large arm that extends beyond the vehicle. A drill at the end of the arm is used to carve out the area of rock. Backhoes work by scrapping away at the face of the rock. They are best suited for use in clayey materials. However, drill and blast techniques are also used where extremely hard rock is encountered and hand trimming may be required to finish the profile. The length of each excavation advance prior to the installation of the support lining depends on the ground conditions. The advance length is shorter in poorer conditions, meaning the lining is installed quicker, which in turn reduces the chance of settlement at the surface. However, the cost of excavating the tunnel is increased where shorter advance lengths are required.

SCL tunnels are often excavated in sections. The tunnel cross section may be split into crown (approximately top 2/6), bench (approximately middle 3/6) and invert (approximately bottom 1/6). The upper sections of the tunnel can be excavated in advance of the lower ones, speeding up the process. In larger tunnels, a central wall may be used to divide the sections so that the excavation is carried out in six stages.

Primary Sprayed Concrete Lining

There are two principal methods of applying the sprayed concrete (shotcrete) lining, dry and wet. In both methods, the shotcrete is pumped to a nozzle from where it is sprayed onto the tunnel roof and walls. Dry shotcrete is batched and pumped dry. It is hydrated by the addition of water at the nozzle. Admixtures are included to accelerate the rate of hardening. Wet shotcrete is batched and pumped wet. The batched concrete contains retarding agents to delay the hardening of the concrete. As the concrete reaches the nozzle, air and an accelerator are added to the mix so that it begins to harden in the air. Recent improvements in admixtures and the development of robotic spraying systems have meant that the wet process has now become the more common method.

The primary sprayed concrete lining provides initial support to the roof and walls of the tunnel. It prevents any loose material or wedges of rock from falling out which may cause instability in the temporary condition. The profile and thickness depend on a number of factors including the quality of the rock and the excavation length. It can be reinforced using steel mesh or alternatively fibres included in the shotcrete mix (either steel or polypropylene).

Permanent Support System

The permanent support of the tunnel roof and walls can be designed in a number of ways, depending on the quality of the rock. Rockbolts can be used in competent rock. Holes are drilled into the tunnel roof and walls and the rockbolts are installed, grouted and tensioned. Where the rock quality is insufficient for rockbolt support alone, steel ribs (sets) can be used. Pre-fabricated structural steel sections are installed against the primary lining and along with the secondary lining form part of the permanent support system. A membrane is usually installed between the two linings to provide waterproofing.

Secondary Lining

The secondary lining is constructed within the primary sprayed concrete lining. It is usually designed to support the full loading on the tunnel. However, improvements in the delivery of shotcrete mean that the primary lining can now be considered as a permanent long-term structural element contributing to the permanent support of the tunnel. This reduces the thickness or amount of reinforcement required in the secondary lining.

The method of construction of the secondary lining is usually one of two types. The most common method is to use movable, reusable formwork to place an in situ reinforced concrete lining, which is ideal for tunnel lengths of uniform size and shape. Alternatively, with the aforementioned improvements in shotcrete mix design, sprayed concrete secondary linings are now being used. These are usually applied with fibre reinforcement and are particularly efficient in areas of varying cross section such as junctions and enlargements in the tunnel as no formwork is required.

Geotechnical Conditions and Constraints

In SCL tunnels, changes in the ground conditions are normally dealt with by using a variety of primary support specifications. The ground at the face (and beyond the face by forward probing) is continuously assessed to enable the amount and specification of primary support to be determined. This may consist of simple fibre reinforced sprayed concrete primary lining to structural steel ribs. The easiest way of dealing with variations in the ground conditions is by reducing the length of the excavation advance. This reduces the amount of time that the excavated tunnel roof and walls are unsupported and thus reduces the risk of settlement or collapse occurring. Varying the section of the tunnel that is excavated in each run is also a commonly used method of dealing with variable ground conditions at the face. Other methods of dealing with varying conditions include:

- Stabilising the excavation face with shotcrete;
- Increasing the thickness of the primary lining or providing temporary structural support;
- Grouting the entire surrounding ground;
- Grouting the face ahead of the excavation;
- Excavating under compressed air conditions;
- Ground freezing ahead of the excavation;
- Dewatering the excavation; and
- Forepoling ahead of the face to provide a support umbrella above the excavation.

SCL tunnels are not suitable for use where water pressures exist due to a high water table. Seepage of water through the walls and roof of the tunnel would lead to difficulties in the shotcrete adhering to the surface of the rock. Where soft ground is encountered with water pressures, a potentially dangerous condition can result as the face of the excavation is likely to fail without support. Methods of dealing with this situation are listed above.

On the Forth crossing, this problem is not expected as SCL tunnels would only be used on each shoreline above the water table in competent rock. The exception to this is excavation of the cross passages under the Firth channel which would be in soft material with high hydrostatic pressures. It is likely that ground freezing or another similar measure would be required to stabilise the excavation face prior to installation of the lining.

Environmental Impacts

It is possible to construct a SCL tunnel without affecting SPA, SSSI, RAMSAR and other designated sites along the riverbanks. However, environmental effects would have to be managed at each portal. The start and finish point of the tunnel is dependant on the ground conditions at the portal, but it can be generally assumed that a minimum of five to ten metres of overburden would be required above the roof of the tunnel. An approach ramp or shaft is therefore generally required at either end of a SCL tunnel.

Removal of significant amounts of excavated spoil may impact on the area surrounding the portals or launch shafts. Spoil may be stockpiled temporarily on site depending on the available space. It may be extracted at either the portal or shaft locations or both, depending on the construction methodology. In any case, it is inevitable that the spoil would need to be transported off-site. Considering the cross section required for the road space, and an average tunnel length for the Forth crossing of 7.5 kilometres, this equates to almost one million cubic metres of spoil to be disposed at each side of the crossing assuming equal amounts of excavation from both ends. This is equivalent to almost two million tonnes or over 65,000 truck movements at each side if all spoil is removed by road which is the most likely option.

Ventilation and Shaft Access

Due to the overall length of the Forth Crossing tunnel, it is anticipated that a fresh air supply would be needed over the full length of the tunnel. This could be accommodated under the road surface if a fully transverse ventilation system is specified, or in a supply duct suspended from the ceiling in a semi-transverse system. This upper duct is used to extract vehicle exhaust fumes in the fully transverse system. Both systems use this duct for removal of smoke in the event of a fire.

The ventilation shafts and emergency access/egress points would be located on the shores of the Forth. These shafts could form the interface between the mined SCL tunnel and a bored TBM tunnel and could be used as potential launch and reception chambers for both a TBM and a roadheader. The shafts would be constructed from ground level and would large enough so that all equipment could be incorporated within the shaft. Shaft details would have no effect on the cross section of the mined tunnel.

Flotation

On the Forth crossing, this problem is not expected as SCL tunnels would only be used on each shoreline above the water table in competent rock. The exception to this is excavation of the cross passages under the river channel. These passages would be constructed at the same level as the TBM tunnel, which has a minimum of two diameters of cover between the top of the tunnel and the river bed. At this depth, there is enough weight of material on the tunnel to counteract the effects of flotation.

Flooding

Construction of the cross passages under the Forth presents a significant challenge in the anticipated soft conditions and high water pressures. A potentially dangerous condition can result as the face of the excavation is likely to fail without support. There are several techniques available to enable the passages to be safely excavated such as ground freezing or working under compressed air conditions.

However, for safety reasons, the design of the mainline TBM tunnels may have to include a provision for watertight bulkheads at intervals along the tunnel during construction to prevent complete inundation of the tunnel in the event of an accident.

Breakdown of Machinery

The process of excavating and lining a SCL tunnel is not as vulnerable to breakdown as a TBM tunnel. The nature and size of the machinery is such that it is easily accessed and repaired if necessary. The equipment is much smaller and cheaper and the whole process is not dependent on any single piece of equipment as the process uses different machinery for different parts of the process. The cutting head of a roadheader should be regularly maintained, and a comprehensive supply of spare parts should be available and easily accessible to the construction site, so that the excavation process is not unduly delayed in the event of a failure.

Approach Ramp Construction

Conventional approach ramps can be used to interface with a SCL portal. The SCL portal generally requires a minimum of five to ten metres of rock over the crown of the tunnel but this is heavily dependent on the quality of the rock and the amount of overlying material. This means that the approach ramp could be in the region of 20 metres deep. Assuming the topography is reasonably level at the portal location, creating a battered cutting to an excavation as deep as 20 metres is not usually feasible given the space required. Where the excavation is in rock, the sides can be cut steeper or retaining walls constructed so that a vertical cut can be obtained and the land take is minimised. Permanent retaining walls up to 20 metres deep would require anchors that would possibly extend beyond the tunnel or road corridor. Given these considerations, it is common to provide a short cut and cover tunnel from the driven portal to a new daylight portal where the height of the permanent retaining walls required is less significant.

Cross Passages

Construction of cross passages is carried out in the same fashion as the mainline SCL tunnel. The same equipment can usually be used depending on the size of the cross passages.

Rate of Construction

The rate of construction of mined SCL tunnels is heavily dependent on the type of material being excavated. Hard rock would tend to slow the process particularly if blasting is required. Conversely, soft material would inevitably cause delays as the excavation advance lengths are shorter and more temporary and permanent support is required. Where ground improvement measures are required, the rate of construction is reduced significantly as the roadheader lies idle while the ground improvements are carried out. Given the relatively small size and manoeuvrability of these machines, they could be diverted to excavate a nearby cross passage while ground improvements are being carried out on the mainline tunnel.

B6.3 Immersed Tube Tunnels

General

Many marine tunnel crossings have been constructed using the Immersed Tube method. This is particularly suited to road tunnel construction as roadways because the cross section can closely follow the required road width and clearance envelope. The carriageways may also be compartmentalised within the same structure, assisting flotation and positioning. In general the approaches to an immersed tube river crossing section are cut and cover tunnels through the river banks, although TBM approach tunnels have been used where topography requires. This is envisaged in the case of the Forth crossing given the environmental sensitivity of the banks. An immersed tube tunnel has been proposed for Corridor E Tunnel only and hence the description of construction methods for the tunnel and approaches are based on this alignment.

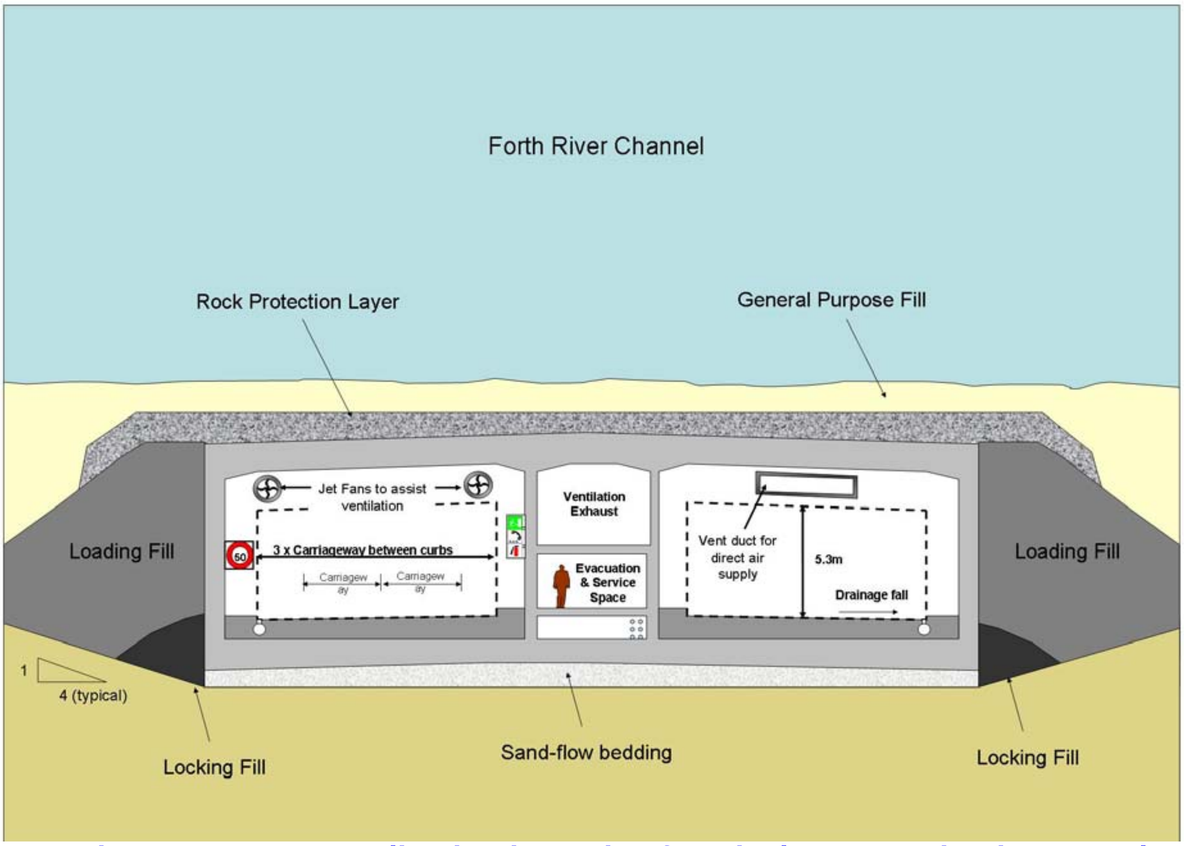


Figure B15 – Generalised Schematic of Typical Immersed Tube Tunnel

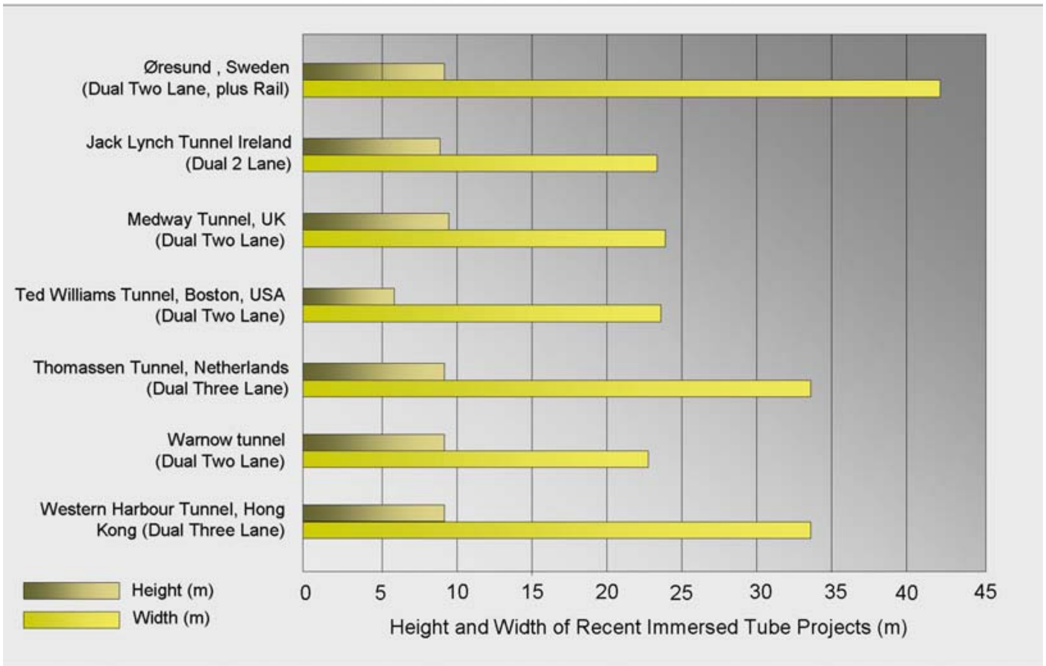


Figure B16 – Range of Immersed Tube Tunnel Sizes for Recent Similar Projects

Construction Methodology

Immersed Tube tunnels are pre-constructed lengths of the tunnel structure that are sunk under controlled conditions into a dredged channel in the seabed or riverbed. They can be constructed in steel using concrete ballast or they can be fully cast in concrete. The selection of the construction materials would be dependant on a number of factors including structural performance, durability, safety and the availability of local skills, materials and construction facilities. They are usually waterproofed externally, which reduces the risk of internal salt damage to the reinforced concrete structures and prevents the waterproofing membranes from being damaged in a severe fire in the tunnel.

There are a number of key elements to the construction process:

Unit size

Immersed tube units may comprise the full tunnel cross section, or may be divided up into adjacent chambers. However, the connection between sections for services and safety can be problematic, particularly if the foundation sediment may cause differential settlement. The length of each element is dependent on a number of design issues including:

- The size of casting facility available;
- The overall length of immersed tube tunnel;
- Vertical and horizontal curvature; and
- Differential settlement of the tunnel foundation layers.

For the Forth crossing, single units of approximately 30 to 40 metres wide and up to 120 metres long would be envisaged.

Unit Fabrication

Generally the production of concrete tunnel units takes place in a dry-dock facility, where single or multiple units are constructed. Casting multiple units has time-saving advantages, but requires more space. The dry-dock required is essentially a large casting facility below the normal water level equipped with lock gates to enable flooding and floating of the units out into position. It must be considered that some extra dredging would be required to allow the units to be transported from the casting basin.

As an alternative the use of steel construction to form the shell of an immersed tube has advantages where there is limited space for a casting basin. There are also likely to be local facilities and skills in shipbuilding that could be used for unit fabrication. The units can be fabricated on slips or hard standings and floated once complete. Steel fabrication includes the installation of any permanent reinforcement bars that are required in structural concrete. Structural and mass concrete are then placed whilst the unit is floating, moored to a jetty.

Bed Preparation

The finished immersed tube tunnel must sit below the riverbed level to protect it from future dredging operations, scour/erosion and ship/anchor impact. Additional depth may also be required to allow modification of the tunnel foundation layers or to accommodate predicted future riverbed scour. The channel required for an immersed tube is therefore a significant underwater excavation operation. Generally conventional pumped or grab dredging would be used, however in areas where harder dolerites or sandstones were present mechanical cutting or blasting may be required. The channel must not only be excavated, but prevented from silting up prior to unit placement; therefore ongoing maintenance dredging may be required throughout construction.

It is common that immersed tubes are constructed in river estuaries that are in urban environments where historic industrialisation has polluted the sea or freshwater. The contaminants remain in the deposited river sediments. As with all underwater excavation these sediments would be released into the river and estuary. If polluted, this would release all the trapped pollution over a relatively short period. Careful site investigation and testing of sediments is needed to identify any potential environmental risks and allow the environmental risks to be managed.

Unit Positioning

Once the tunnel units are fabricated and the channel prepared, the tunnel units are sealed with temporary bulkheads. The units can either be designed as positively or negatively buoyant. For positive buoyancy unit, water would be pumped into ballast tanks in the unit to make it sink, with mass concrete placed through the connected open tunnel to hold the unit in placed before fit out of the structure. When designed as negatively buoyant structures, the units would only float with the assistance of barges on either side. The barges are used as a platform to lower the units into position. Positive buoyancy is generally preferred as there is inherently less risk of losing a unit due to ship collision or unforeseen incidents.

Positioning may be assisted by anchor cables secured to the seabed, particularly where strong tides are present. Once in position, the tunnel unit is lowered into position against the preceding unit. It is common practice to place a sand bed beneath the unit when it is in position. The sand is passed through pipes cast into base and side walls of the units. In these conditions the sand is self compacting. The joints between the units are formed by the use of omega shaped rubber gaskets. The joint is compressed by removing the water between adjacent bulkheads. Water pressure on the exposed end of the placed unit compresses the joint against the previously installed unit.

Fill/Armouring

When all units are secured, the fill and armouring is constructed to protect the tunnel from ship and dredging impact and to assist in holding the tunnel in position once the water ballast tanks within the unit are drained. Internal fit-out of the tunnel roadway and internal systems may then commence.

Geotechnical Risks and Constraints

Immersed tube tunnelling relies on the ability to excavate and maintain a large open channel in the riverbed. Heavy siltation from strong tides or very soft sediments can lead to problems maintaining the channel. Although sampling and testing would be required, from initial observations, the river sediments do not appear to present a problem for an immersed tube tunnel.

Channel excavation to receive the immersed tube tunnel units is generally carried out by dredging. If hard rock like dolerite is encountered, then blasting may be required. Underwater blasting is undesirable and can significantly increase environmental impact, cost and construction duration.

Environmental Impacts

Construction of immersed tubes require significant disturbance of the sediments along and adjacent to any alignment. As the Forth has a long history of industrial and commercial operations upstream of any potential crossing there may be trapped pollutants within the existing sediments. While these may not necessarily represent a hazard, the excavation of large amounts of sediment from dredging may release any pollutant in a relatively short period and therefore in a concentrated form.

The banks of the Forth are almost entirely designated as SPA or SSSI. Although the construction of an immersed tube may not necessarily directly affect these areas, sediment release from construction is likely to affect them at least in the sort term during construction. Where the landfall of a proposed immersed tube tunnel lies within a protected area, the approach structures are likely to be TBM tunnels as the more conventional cut and cover approach tunnels would have a direct impact on the banks, shoreline and littoral zone.

Blasting is likely to be required to remove any dolerite that is encountered along the alignment. Underwater blasting is undesirable and can significantly increase environmental impact.

Ventilation and Shaft Access

Due to the overall length of the Forth Crossing tunnel, it is anticipated that a fresh air supply would be needed over the full length of the tunnel. This could be accommodated in two external cells if a fully transverse ventilation system is specified or in the central cell in a semi-transverse system. This central duct is used to extract vehicle exhaust fumes in the fully transverse system. Both systems use this duct for removal of smoke in the event of a fire.

The ventilation shafts and emergency access/egress points are located on the shorelines in the approach tunnels, and hence have no direct effect on the immersed tube section of the tunnel.

Flotation

Immersed tube tunnel units are usually constructed so that they are positively buoyant. The units are positioned on a prepared formation in a dredged channel in the riverbed such that the roof of the tunnel is a minimum of five metres below the river bed. Water is pumped into ballast tanks to bring the units into place. More water is then added into ballast tanks in the unit to make it sink into position. The formation may be a prepared gravel bed, but, depending on the conditions, it may consist of isolated pad or piled footings. Sand is passed through pipes cast into base and side walls of the units to create a uniform support base.

Ballast concrete is then poured and fill material is placed around and on top of the units to secure them against flotation. The units are designed so that the weight of the ballast concrete and the backfill material is sufficient to prevent flotation of the units after the water in the ballast tanks is drained. Interlock and friction between the backfill material and the side walls of the tunnel units provides further assistance in holding the tunnel in place. The backfill also provides protection to the top of the units from erosion and scour along with ship and dredging impact and damage from trailing anchors etc.

Flooding

It is often assumed that the process of building a tunnel in water, rather than boring through the ground beneath it would increase the likelihood of flooding or leakage. In fact, immersed tube tunnels are nearly always much drier than bored tunnels, due to the above-ground construction of the elements in a controlled environment. Underwater joints between units use robust rubber seals which have proved extremely effective in dozens of tunnels to date. The primary flooding risks associated with the construction of immersed tube tunnels would be failure of the temporary seals and bulkheads during the positioning of the units. Watertightness at the interface with the approach tunnels is another significant design issue.

Breakdown of Machinery

There are no serious problems associated with the breakdown of machinery in immersed tube construction as the process does not rely heavily one a single piece of equipment as is the case in bored tunnels.

Approach Ramp Construction

The conventional method for constructing approach tunnels to an immersed tube tunnel is to use the cut and cover method from each river bank. This would involve the construction of cofferdams at each river bank, where the last immersed unit would meet the cut and cover unit. This involves considerable disruption to the river banks, and given that the shorelines of the Forth are designated as SPA or SSSI in many locations, the use of cut and cover approach tunnels may not be considered for this crossing.

Given the riverbank topography and its environmental sensitivity on Corridor E, a TBM tunnel would be used as approaches to the immersed tube tunnel on this corridor. The interface between the immersed tube and the TBM is located at the edge of the deep channel. The interface is likely to require the construction of a large caisson or cofferdam to provide a dry working area for the interface. Where the side walls of the channel rise quite sharply so it may be assumed that the rockhead profile closely follows the side of the deep channel. In this instance, construction of the cofferdam may incorporate the side wall of the channel with some trimming and excavation of rock to create a suitable vertical face for the TBM breakthrough. A soft eye would be constructed in the outer wall of the cofferdam which is broken through once the immersed tube units have been placed and sealed against the cofferdam. Where the walls of the deep channel are not as steep, a fully enclosed caisson or cofferdam may be required with soft eyes on both sides for breakthrough by the TBM on one side and through to the attached immersed unit on the other. Given that the TBM needs approximately two diameters of cover above the crown of the tunnel, a significant amount of dredging would be required to obtain the required depth for the immersed units and for the cofferdam itself.

A special cast in situ connection unit needs to be cast in the cofferdam to transition the tunnel from the circular cross section of the TBM to the rectangular shape of the immersed tube units. This affects both the traffic envelopes and the location of all services within the unit including but not limited to the fresh air and exhaust ducts.

An alternative construction technique used at the interface between an immersed tube tunnel and a TBM tunnel is to provide a large tremmied concrete plug, or soft eye, that the TBM would excavate into until breakthrough into a reception chamber in the first immersed tube unit that is butted against the plug. The TBM lining is installed and sealed against the plug. The first immersed tube unit needs to be a special unit to transition between the two different shapes and to allow the services to change position to suit the different tunnel shape.

The TBM tunnel generally requires a minimum of two diameters of cover, which means that a considerable amount of dredging is required for placement of the concrete plug and the first/last units of the immersed tube.

Cross Passages

Cross passages can be easily accommodated in immersed tube sections. The units would have a central cell for a smoke extraction/exhaust duct and other services. Cross passage would consist of fire doors from the central cell to the main cells containing the carriageways.

Rate of Construction

The advantage of immersed tube tunnels is that they do not rely on a single operation as is the case in bored tunnels. Immersed tunnelling creates three operations - dredging, tunnel unit construction and tunnel installation. These can take place concurrently, thus moderating programme risk considerably. Partly for this reason, an immersed tunnel is generally faster to build than a corresponding bored tunnel. It is however dependant on the availability and proximity of a suitable casting basin. The size of the casting basin would determine the size of the units and the number that can be constructed at any one time.

B6.4 Cut and Cover (C&C) Tunnels

General

Cut and cover tunnels are similar to immersed tube tunnels in that they are shallow tunnels constructed in a trench. C&C tunnels are primarily land-based and are not suited for deep river crossings. They have been used in shallow marine environments and could therefore be considered for littoral and shallow sub-littoral zones, although the environmental impact of such construction on a sensitive shoreline such as the Forth may rule out the use of C&C tunnels in such an environment. In this instance, both the topography and the sensitivity of the shoreline on the alignment of the three proposed tunnels have precluded the use of C&C tunnels for this purpose. C&C tunnels are proposed near some of the portals where the topography requires or there is insufficient rock cover for a bored or mined tunnel to form a daylight portal or where the retained height or battered excavation footprint is excessive.

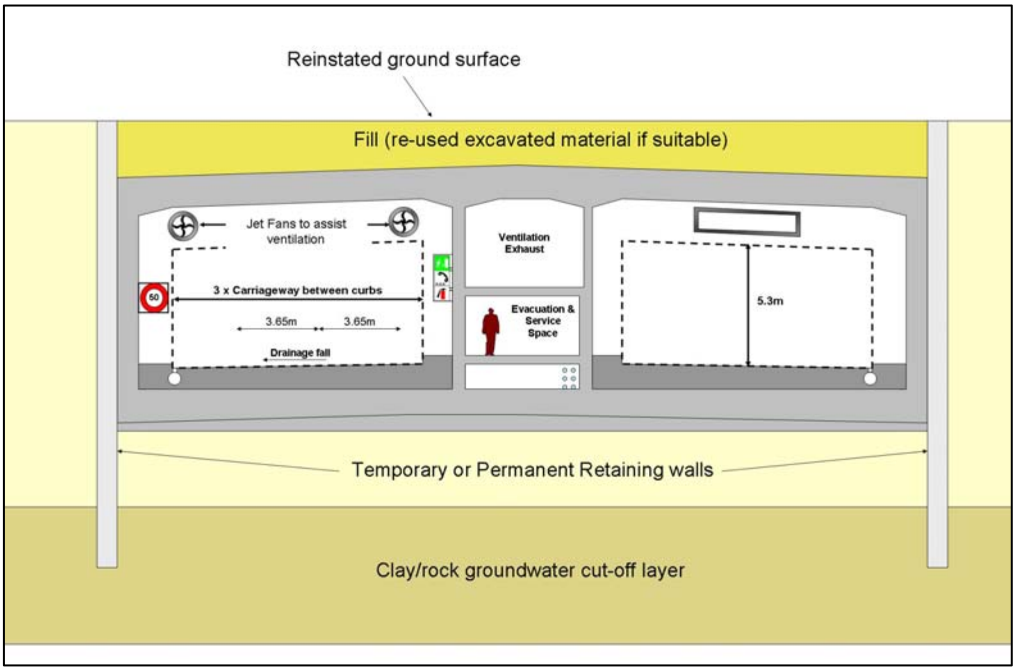


Figure B16 – Generalised Schematic of Typical Cut & Cover Tunnel

Construction Methodology

The construction sequence for a cut and cover tunnel falls into the following stages:

Excavation and Support

The initial "cut" is done using similar methods as per road cuttings. Prior to excavation, buried utilities and services crossing the route have to be protected or diverted. Permanent utility diversions are used to avoid the tunnel alignment where possible. When this is not possible these utilities may be temporarily raised over the alignment clear of construction. For gravity sewers this may involve pump installation.

The cut is constructed in a number of ways, depending on the support requirements of the ground. In hard rock this may be vertical walls supported by rock bolts and sprayed concrete and in soft rocks and soils, stable slopes may be created by excavating benches or batters. If surface space is restricted, or the disturbance caused by construction needs to be minimised then retaining walls can be used to stabilise the excavation. These may be permanent and incorporated into the final structure or temporary and removed after the tunnel structure has been completed. Anchors or struts are used to provide temporary support to the retaining walls until the tunnel floor and roof slabs are cast.

Tunnel Fabrication

Once a stable open cut has been constructed, the tunnel structure is fabricated in the trench. This structure is generally constructed from reinforced concrete using large forms. Once the tunnel floor and roof slabs are cast, temporary struts can be removed or temporary anchors de-stressed. The tunnel roof could also consist of bridge beams placed on the tunnel walls that act as abutments. The use of precast concrete arch roof structures is becoming more commonplace in C&C tunnels.

Reinstatement

After construction, fill is used to reinstate the ground surface. Where possible this fill may be reserved material from the trench excavation. Additional material may be required to assist with compaction and drainage, or if the trench material is unsuitable. Reinstatement may be to the original topography and land use, but in some cases it offers the opportunity to improve surface conditions, such as utility and drainage improvements or local road upgrades.

Geotechnical Conditions and Constraints

The ground conditions dictate the amount of temporary support that is necessary during the initial excavation. In competent rock, the excavation could be vertical with rock bolts and sprayed concrete and in soft rocks and soils, stable slopes may be created by creating benches or batters. If surface space is restricted, or the disturbance caused by construction needs to be minimised, then retaining walls can be used to stabilise the excavation. The ground conditions would play a similar role in determining the structural size of the floor slab and walls as these elements are subject to lateral soil pressures and upheaval.

Environmental Impacts

Construction of C&C tunnels involves disruption to the complete footprint of the proposed tunnel. While the disruption is temporary, it can have a significant impact on the environment depending on the location. C&C tunnels are often used as approach structures to immersed tube tunnels, and the effect of the river bank or shoreline can be significant in this instance. Given the environmental sensitivity of the banks of the Forth, C&C tunnels have not been considered for use as approaches to the immersed tube tunnel on Corridor E. C&C tunnels have only been anticipated where the depth of the bored tunnel portals would require a significant land take for battered or benched excavations or retaining walls that are conceivably too high. Construction of C&C tunnels in this instance would decrease the visible footprint of the approach ramps, thus reducing the environmental impact of the tunnel. Along with being unsightly, deep open excavations can be a safety hazard. In other instances, the geology may require that the bored or mined tunnels terminate short of the ultimate daylight portal location where there is insufficient rock cover above the crown.

Ventilation and Shaft Access

Due to the overall length of the Forth Crossing tunnel, it is anticipated that a fresh air supply would be needed over the full length of the tunnel. The structure of the C&C tunnel would be similar to the immersed tube so the fresh air duct could be accommodated in two external cells if a fully transverse ventilation system is specified or in the central cell in a semi-transverse system. This central duct is used to extract vehicle exhaust fumes in the fully transverse system. Both systems use this duct for removal of smoke in the event of a fire.

The ventilation shafts and emergency access/egress points are located on the shorelines in the bored and mined tunnels, and hence would have no direct effect on the C&C sections of the tunnel.

Flotation

C&C tunnels by nature usually have sufficient self weight and overburden pressure to prevent flotation. However, in ground conditions with a high water table, the design would have to cater for the effect of flotation and upheaval forces on the base slab.

Flooding

Flooding is generally not an issue with C&C tunnels unless constructed in a marine environment. Where they are used as approach structures to immersed tube tunnels, a cofferdam is usually constructed to hold the water during construction of the tunnel structure.

Breakdown of Machinery

There are no risks associated with the breakdown of machinery in C&C tunnel construction as the process does not rely heavily one a single piece of equipment as is the case in bored tunnels.

Approach Ramp Construction

Conventional approach ramps are usually used to interface with C&C tunnels. The approach ramps could be in an open cutting but it is normal to provide conventional retaining walls at the sides of the approach ramps.

Cross Passages

Cross passages can be easily accommodated in C&C tunnels. The units may have a central cell for a smoke extraction/exhaust duct and other services. Cross passage would consist of fire doors from the central cell to the main cells containing the carriageways, or, alternatively, where a central cell is not required for services and ventilation, a single central wall may be provided between the vehicle spaces with doors.

Rate of Construction

The advantage of C&C tunnels is that they do not rely on a single operation as is the case in bored tunnels. C&C tunnels have three key activities: excavation and support, structure fabrication and reinstatement. These can take place concurrently for a reasonably long tunnel, thus moderating programme risk considerably. Cut and cover is usually the quickest method of tunnelling, as there is a lesser chance of encountering unexpected conditions, and this form of construction is not as specialised as conventional underground tunnelling because it is often similar to surface road and civil works.

B7 CORRIDOR SPECIFIC ISSUES

B7.1 Corridor C Tunnel

Introduction

The proposed tunnel on Corridor C is approximately 8.5 kilometres long. The alignment and profile are shown on Drawing Number T/BC1/01. The southern portal and toll plaza (if required) is located immediately to the south of the M9 adjacent to the disused Craigton Quarry. The proposal involves an open cutting to accommodate the toll plaza (if required), with retaining walls forming the approach ramp to the tunnel portal at Chainage 2300. A mined SCL tunnel is proposed from the portal until Chainage 4900, where a ventilation shaft is located near the shore to the south of Wester Shore Wood. Under the Forth a bored TBM tunnel is proposed from Chainage 4900 to 9300 where the second ventilation shaft is proposed to the south of the A985. From here, a mined SCL tunnel is envisaged as far as the portal at Chainage 10800, where a short C&C tunnel is anticipated to limit the land take and footprint of the cutting required for the approach ramps. This also helps to limit the size of permanent retaining walls required to form the approach ramps.

Constructability Issues

There is quite a large area at the southern portal for a construction compound. An open cut decline to the portal can be constructed without disruption to the M9 or the railway line. The limited geotechnical information available suggests that, apart from a few metres at the top, this ramp would be excavated in rock, so a relatively steep open cut should be possible. A TBM can be launched from the approach ramp if required. However, the geotechnical data available suggests that a roadheader could be used for this section of tunnel as far as the shore.

Similarly on the northern side, a mined tunnel could be constructed from the portal to the shoreline. The northern ramp may require open cut retaining walls and a short cut and cover tunnel to limit the land take and avoid disruption to the property at Blackhall on the north-western corner of the site. This helps to reduce the visual footprint of the approach ramps. At the same time as construction of the mined tunnels from the portals, other worksites could be set up near each shore and used to launch TBMs in both directions through deep shafts that would ultimately be used as ventilation stations and emergency access/egress points.

A TBM is more suited to tunnelling under the Forth due to the presence of soft river sediments. However, if a combination of soft sediments with very hard dolerite in the Firth crossing were encountered this may be problematic. A large diameter TBM designed for soft sediments is unlikely to be able to excavate in hard rock and vice versa. It is likely that any large areas of dolerite would be excavated from the surface by constructing a caisson or cofferdam and mining through the dolerite by drill and blast or other suitable means. A comprehensive site investigation is required to identify zones of dolerite. However, based on the limited data available, large areas of dolerite are not expected to be encountered on this alignment.

There is a significant risk of encountering old mine workings in the area to the south of Wester Shore Wood where the ventilation stack and construction compound is situated.

It is also possible that unexpected obstructions may be encountered in the glacial and alluvial deposits. These may include large boulders, trees or volcanic sills and dykes that are buried in the Firth sediments. A large diameter EPB TBM designed for soft sediments is unlikely to be able to excavate through these and intervention at the cutting face may be required. Given the hydrostatic pressure, this would have to be carried out under compressed air conditions. This would require decompression facilities and would cause a considerable delay in the construction programme.

Construction of cross passages under the Firth represents a significant challenge. A special lining segment can be installed at the cross passage location to act as a soft eye which is then mined through. Mining in soft sediments with groundwater pressure presents difficulties as the face of the excavation is unsupported during construction. Ground improvement techniques such as ground freezing would be required.

Excavation and transport of significant amounts of excavated spoil may impact on the area surrounding the portals and ventilation shafts. It is expected that approximately one million cubic metres of spoil would be generated at each side of the crossing assuming equal amounts of excavation from both ends. This is equivalent to over two million tonnes or over 70,000 truck movements at each side if all spoil is removed by road which is the most likely option.

The BP Kinneil to Dalmeny oil pipeline crosses the proposed alignment to the north of the M9. The tunnel is approximately 40 metres underground in competent rock at the crossover point and, provided vibration and settlement are controlled, construction of the tunnel should not adversely affect the pipeline.

Construction and Ventilation Shaft Sites

Potential construction sites have been identified and are shown on Drawing Number T/GC1/01. The sites are at the tunnel portal and ventilation shaft locations because permanent above ground structures need to be constructed there.

The northern portal construction site is a level greenfield site with access to the A90 and M90 via Admiralty Road or the A823. The approximate dimensions of the site are 320 metres wide by 550 metres long. A section of the local road leading from Blackhall Farmhouse onto Grange Road may need to be diverted prior to construction. This diverted road would form the northern perimeter of the proposed construction site. Off site disposal of tunnel spoil by road is aided by the proximity of the A921, A90, A985 and M90.

The shaft construction site on the northern shore is a greenfield site directly north of the remains of Rosyth Church. The site with approximate dimensions of 500 metres by 250 metres ranges from 10 metres above sea level at the shore to 40 metres above sea level at its highest point. A new access road to the site is required from a point along Admiralty Road. This would serve as the permanent access road to the ventilation station and for maintenance and emergency services during the operation of the tunnel.

The proposed southern portal construction site is adjacent to the disused Craigton Quarry. The site is bounded on the northern side by the M9 and on the southern perimeter by the railway line. The approximate dimensions of the site are 780 metres by 300 metres. Access to the site could be from a point on Beatlie Road. Alternative methods of spoil disposal using Union Canal or the adjacent railway line are feasible, and disused quarries in the surrounding area could be used as stockpile sites.

The shaft construction site on the southern shore is approximately 500 metres by 600 metres and is reasonably level. A new access road is required from the site to the local road which joins up to the A904. A permanent ventilation structure needs to be located on the site and the adjacent forest area would reduce the visual impact of this structure.

Horizontal and Vertical Alignments

The horizontal alignment of the tunnel is constrained by a number of factors including, but not limited to, the location of the portals (and toll plaza, if required, on the south side), the need for ventilation shafts on each shoreline, and the required connections to the road network and their performance against the objectives of the Forth Replacement Crossing Study. It is also necessary to maintain a minimum radius of 1020 metres on horizontal curves to achieve the required stopping sight distances. In choosing the location of the portals, it has been noted that a large construction compound would be located there and that sufficient space and access was required. Similarly at the ventilation shaft locations near the shorelines, the sites were chosen to minimise the environmental impact of both the construction compound in the short term and the ventilation station in the permanent condition.

The preliminary design concluded that the southern tunnel portal and toll plaza (if required) should face east to achieve better connections with the road network. The alignment of the bored TBM tunnel under the Firth was kept as straight as possible so that the stopping sight distances could be achieved without the need to alter the cross section. The minimum horizontal curve was introduced in the mined SCL tunnel section on each shoreline as this tunnelling method provides greater flexibility in terms of increasing the cross section if necessary.

The vertical alignment is derived from maintaining a minimum of two diameters of cover above the bored TBM tunnel under the Forth. The depth of the Firth and the need to rise to make the road network connections mean that the vertical alignment is maintained at three per cent, which is the recommended maximum gradient for road tunnels in European Tunnel Regulations.

The preliminary design considered locating the southern portal and toll plaza (if required) on the northern side of the M9. However, the gradient of the tunnel in this configuration was excessive and, given the location of Duntarvie Castle, there was insufficient space for the toll plaza (if required) and the road network connections.

At the portals, the vertical alignment aimed to keep one diameter of cover over the tunnel, which is the minimum for a TBM portal. By using a mined SCL tunnel, it may be reduced, but this is dependent on the quality of the rock above the crown of the tunnel. In the event of poor ground conditions at the portals, a short cut and cover tunnel can be constructed until sufficient rock cover is achieved. This would not affect the vertical alignment of the tunnel.

Road Network Connections

Details of the road network connections for Corridor C Tunnel are covered in Section 4.3.4 of Volume 1 Main Report.

Geotechnical Conditions

Investigation of the limited available geotechnical data indicates that the tunnel must negotiate limestone, shales, sandstones and coal measures on both banks of the Forth. It is likely to encounter soft alluvial sediments and glacial deposits under the Firth with mudstones and siltstones at the interface.

There is also a possibility of encountering hard dolerite rock. Although there are no specific outcrops in the Firth on this corridor to indicate the presence of dolerite, the dolerite under the nearby Blackness castle indicates that outcrops are in the general vicinity. There is very little information available regarding the rockhead contours under the Forth, so an indicative geotechnical cross section has been developed with a conjectured rockhead profile. This is shown in Figure B17.

It is likely that high groundwater pressures would be encountered in the river sediments. There is a significant risk of encountering old mine workings in the area to the south of Wester Shore Wood, where the ventilation stack and construction compound are proposed.

Sandstone, shale, and coal are generally suitable materials for mining, as this technique is suited to competent rock that can support itself until the excavation pass is complete and the lining is installed, but is also not too hard so that it can be readily excavated by roadheader or similar means. Where harder rock, for example limestone, is encountered, drill and blast techniques may be required.

Borehole logs close to the alignment of the tunnel on both banks of the Forth suggest that the rockhead is shallow. The topography of the area reinforces this with steep cliff-like shorelines rising from the water. Mining generally requires a minimum of five to ten metres of rock cover depending on the quality of the rock and amount of overburden, so with the possible exception of the portals where the tunnel approaches the surface, this cover should be readily achieved.

Due to its suitability for the anticipated conditions and its lower relative cost, mining is recommended as a suitable method for tunnel excavation on both sides of the Forth based on the limited geotechnical data available. However, it should be noted that this needs to be confirmed by a detailed site investigation to confirm the type, quality and depth of rock along the proposed alignment.

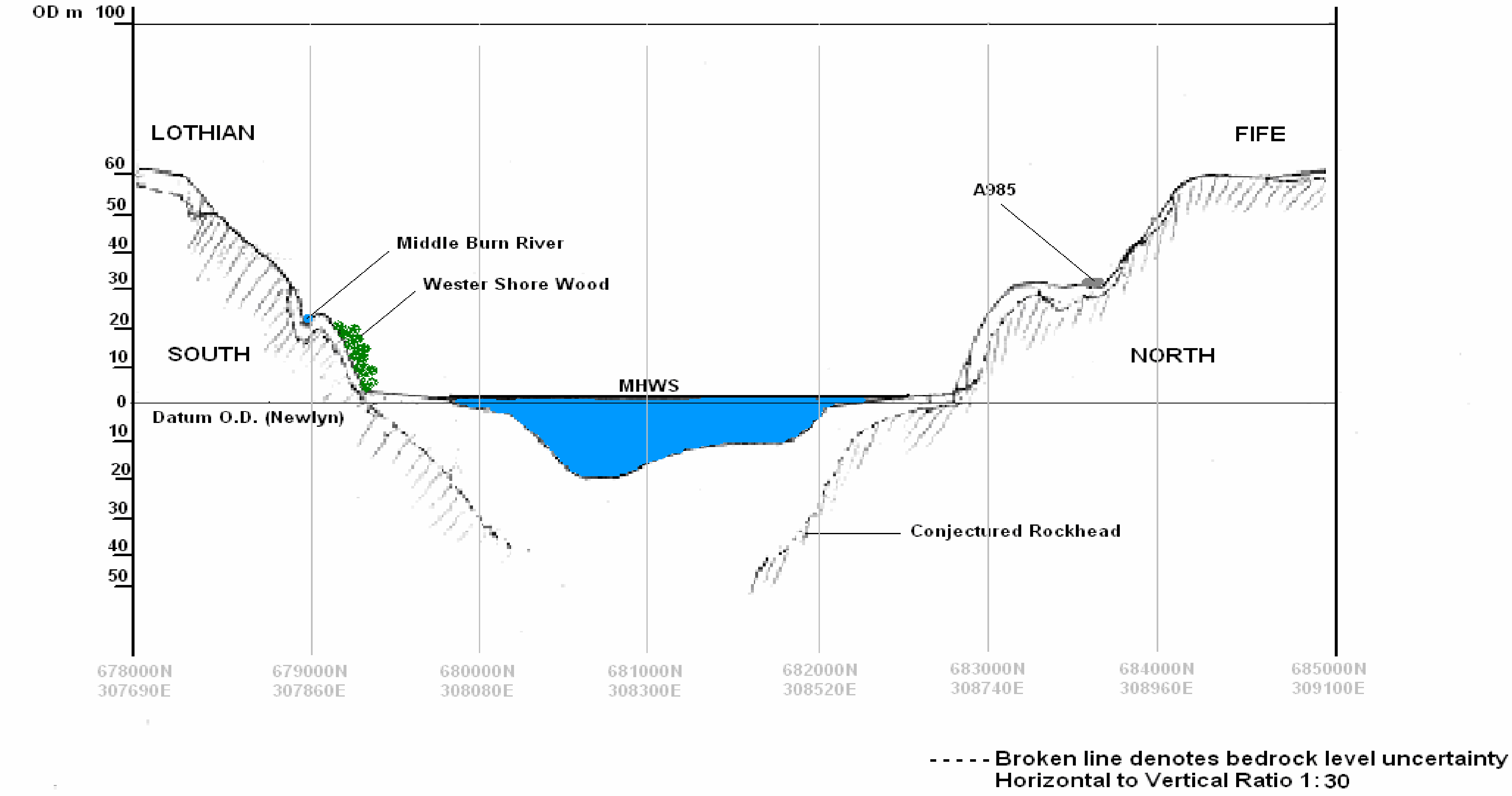
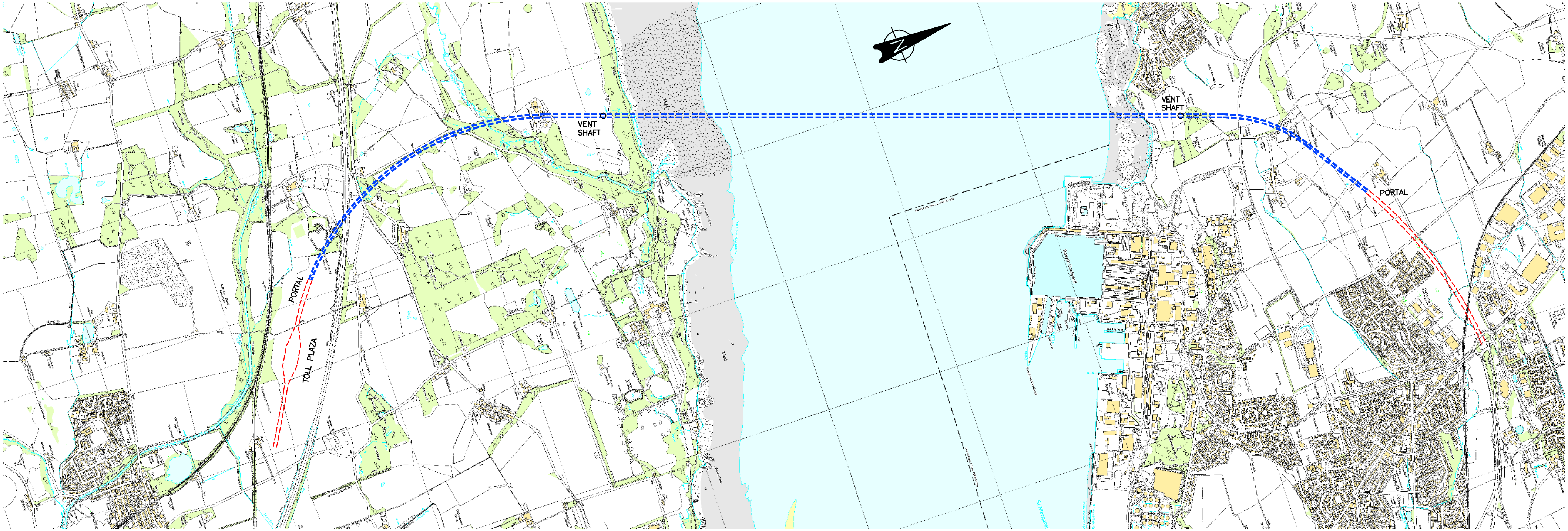


Figure B17 – Corridor C - Indicative Geological Cross Section

Cost Estimates

Cost estimates for the construction of the Corridor C Tunnel have been derived from a bottom up costing approach. Section 5.0 of this report discusses the approach used in more detail. A summary of the costs are contained in Section 5.10 of the Volume 1: Main Report.



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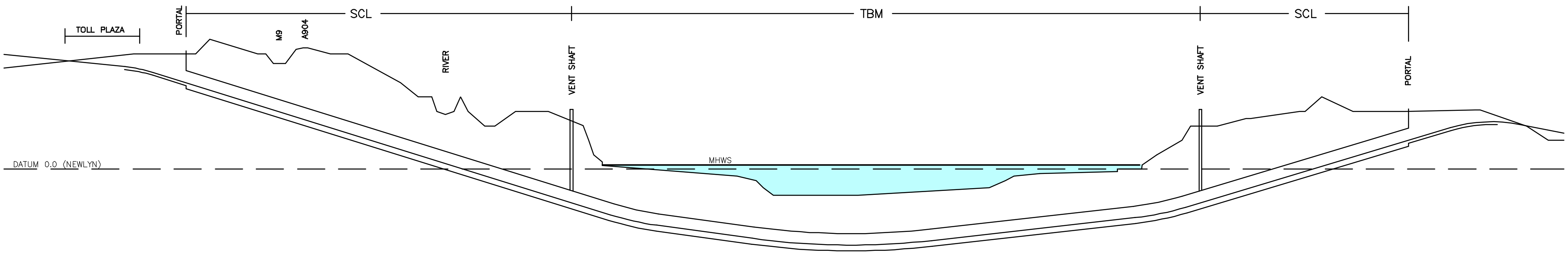


PROFILE VERTICAL / HORIZONTAL DISTORTION 10:1

CORRIDOR C TUNNEL

FIGURE B18

B7.2 Corridor D Tunnel

Introduction

The proposed tunnel on Corridor D is approximately 7.3 kilometres long. The alignment and profile are shown on Drawing Number T/BD1/01. The southern portal and toll plaza (if required) are located to the north of the M9 adjacent to the Humbie Quarry and Reservoir. The proposal involves an open cutting to accommodate the toll plaza (if required) and the tunnel approach ramp. A mined SCL tunnel is proposed from the portal at Chainage 2350 until Chainage 3900, where a ventilation shaft is located near the shore to the southeast of East Shore Wood. Under the Forth, a bored TBM tunnel is proposed from Chainage 3900 to 7500 where the second ventilation shaft is proposed in disused land to the west of St. Margaret's Marsh. From here, a mined SCL tunnel is envisaged to the portal at approximate Chainage 9650 immediately to the south of the A921 (Admiralty Road) and north of Inverkeithing.

Constructability issues

A large cutting is required on the southern side between five and 10 metres deep to accommodate the toll plaza (if required). The vertical alignment of the tunnel dictates that this area must be excavated. Some environmental impacts may unavoidable due to the scale of the cutting. However, this is likely to be offset by the fact that the toll plaza, if required, would be hidden from view. The area at the southern portal and toll plaza (if required) is suitable for a construction compound. A TBM can be launched from the approach ramp if required, however, based on the limited geotechnical data available, it is envisaged that a roadheader could be used for this section of tunnel as far as the riverbank. Similarly on the northern side, a mined SCL tunnel could be constructed from the portal to the shoreline. At the same time as construction of the mined tunnels from the portals, other worksites could be set up at the ventilation shaft locations which can be used as reception and launch chambers for TBMs.

A TBM is more suited to tunnelling under the Forth due to the presence of soft glacial and alluvial sediments. However if a combination of soft sediments with very hard dolerite in the Firth crossing were encountered this may be problematic. It is likely that hard dolerite rock would be encountered along this corridor as outcrops such as Beamer Rock demonstrate that there are dolerite intrusions in the area. This would need to be confirmed by a detailed site investigation before the alignment was finalised. A large diameter TBM designed for soft sediments is unlikely to be able to excavate in hard rock and vice versa. It is likely that any large areas of dolerite would be excavated from the surface by constructing a caisson or cofferdam and mining through the dolerite by drill and blast or other suitable means.

It is also possible that unexpected obstructions may be encountered in the glacial and alluvial deposits. These may include large boulders or trees that have remained in the Firth sediments. A large diameter EPB TBM designed for soft sediments is unlikely to be able to excavate through these and intervention at the cutting face may be required. Given the hydrostatic pressure, this would have to be carried out under compressed air conditions. This would required decompression facilities and would cause a considerable delay in the construction programme.

Construction of cross passages under the Forth represents a significant challenge. A special lining segment can be installed at the cross passage location to act as a soft eye which is then mined through. Mining in soft sediments with groundwater pressure presents difficulties as the face of the excavation is unsupported during construction. Ground improvement techniques such as pre-grouting blocks from a jack-up barge or ground freezing would be required.

Excavation and transport of significant amounts of excavated spoil may impact on the area surrounding the portals and ventilation shafts. It is expected that approximately 850,000 cubic metres of spoil would be generated at each side of the crossing assuming equal amounts of excavation from both ends. This is equivalent to over 1.7 million tonnes or over 55,000 truck movements at each side if all spoil is removed by road which is the most likely option.

The BP Kinneil to Dalmeny oil pipeline crosses the proposed alignment approximately 750 metres north of the southern portal. The tunnel is approximately 35 metres underground in competent rock at the crossover point and provided vibration and settlement are controlled, construction of the tunnel should not adversely affect the pipeline.

Construction and Ventilation Shaft Sites

Potential construction sites have been identified and are shown on Drawing Number T/GD1/01. The sites are at the tunnel portal and shaft locations because permanent above ground structures need to be constructed there.

The proposed construction site for the northern portal is the greenfield site directly north of the residential areas of Inverkeithing to the south of the A921 (Admiralty Road). The site is approximately 250 metres by 125 metres. Access is from the B981 or the A921 (Admiralty Road) allowing traffic direct access to the A90.

The shaft construction site on the northern shore is the area adjacent to St. Margaret's Marsh. This area has been safeguarded for construction and operation of a replacement Forth crossing as part of the Rosyth Dock Development Plan. It is a level greenfield site approximately 500 metres by 250 metres. Access to this site is possible by land or water.

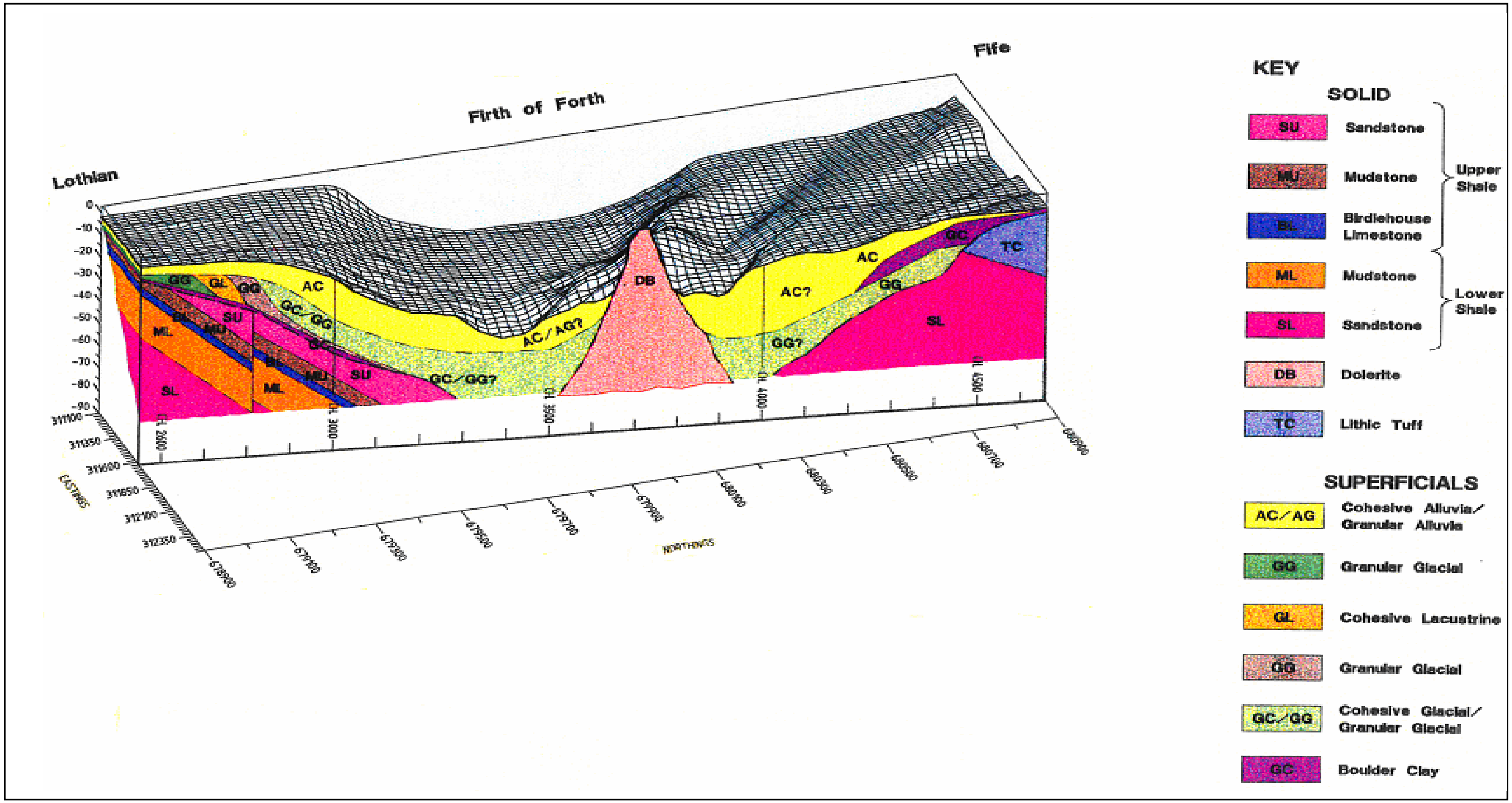


Figure B19 – Corridor D - Indicative Geological Cross Section

The southern portal construction site is in the area of the proposed toll plaza (if required). It is a slightly sloped greenfield site approximately 750 metres by 500 metres. The proximity of the site to the water reservoir in the south eastern corner would require particular care during construction. A site entrance can be located on Builyeon Road allowing access to the A904 and ultimately the A90.

The shaft construction site on the southern riverbank slopes up from the Firth to a peak of 80 metres above sea level. The site is bisected by a local access road and an alternative route for local traffic may need to be established prior to construction. The site is approximately 400 metres by 500 metres and has an entrance on to the A904 which allows direct access to the A90.

Horizontal and Vertical Alignments

The horizontal alignment of the tunnel is constrained by a number of factors including but not limited to the location of the portals (and toll plaza, if required, on the south side) and the required connections to the road network and their performance against the objectives of the Forth Replacement Crossing Study. It is also necessary to maintain minimum radii on horizontal curves in order to satisfy stopping sight distances. The chosen alignment also considered the requirement for ventilation shafts at the shorelines and looked to avoid any environmentally sensitive areas. It also considered the likelihood of these shafts being used as reception and launching chambers for TBMs.

On the south side, disruption to the covered reservoir and the water filled Humbie Quarry might be avoided whilst a single crossing of the open Humbie Reservoir has been chosen at the narrowest point. A number of properties close to the possible toll plaza and tunnel portal area are also avoided, and, whilst there may be some disruption during construction, the properties would be largely unaffected by the works.

The horizontal alignment takes into account the requirement for ventilation shafts on each shoreline. Suitable sites are located adjacent to the heliport site on the south shore and next to the disused oil storage depot on the north shore just west of St. Margaret's Marsh.

The vertical alignment is derived from maintaining a minimum of two diameters of cover above the TBM tunnel under the Forth. A key feature of the crossing is the deep channels adjacent to Beamer Rock. These extend to depths of approximately 30 metres below sea level. Therefore the tunnel under the Forth would be approximately 20 to 25 metres below riverbed level at its deepest point in the Firth. The tunnel must then rise to meet network connections at the M90 and M9 that are of the order of 60 metres above sea level.

On the southern side, the topography rises to approximately 80 metres above sea level before falling towards the Firth. It is desirable to keep any possible toll plaza on the northern side of the M9 to reduce the amount of land take and road links required to tie back into the M9. This means that it is necessary to increase the tunnel gradient to four per cent and to place the possible toll plaza in a cutting approximately five to ten metres below the surrounding ground. As such, the tunnel approach ramp would begin immediately to the north of the railway line after the approach road spans over the reservoir. At the southern end of the toll plaza (if required) it is anticipated that the road surface would be approximately five metres below the existing ground level. The gradient at the possible toll plaza is approximately one per cent with the portal approach ramp steepening to four per cent to match the tunnel.

The increase in tunnel gradient above three per cent may require additional safety measures in accordance with the EU Road Tunnel Safety Regulations 2007 Consultation Draft. Additional safety measures may include:

- Enhanced ventilation (up to and including additional ventilation shafts and plant);
- Reduction in tunnel vehicle speed and/or traffic volume to reduce risk of congestion; and
- Control and limitation of the number and type of HGV utilising the tunnel.

These regulations are in consultation at present, due for implementation during 2007. However, the current text of the regulations forms the basis for the alignment concepts presented in this report. At this stage of the design process it is difficult to assess the cost impact of the steeper gradient. However, at a maximum of four per cent, and given that the horizontal alignment is straight in this location, it is envisaged that it would not be prohibitive. Should this option be carried forward the design would be optimised find the balance between the reduced costs of a shorter, steeper tunnel alignment and the increase in safety measures that may be required.

It is noted that an option similar to this was considered for Corridor C. However, due to topography north of the M9 in that area the necessary vertical gradient required for making this achievable was significantly more than four per cent and this was considered prohibitive.

The gradient remains at a maximum of three per cent on the northern side.

Road Network Connections

Details of the road network connections for Corridor D Tunnel are covered in Section 4 of Volume 1 Main Report.

Geotechnical Conditions

Investigation of the limited geotechnical data available indicates that the tunnel must negotiate sandstones, shales and coal on the southern bank of the Forth and predominantly sandstone and dolerite rock on the north bank. The tunnel is also likely to encounter soft alluvial sediments and glacial deposits under the Firth. There is a significant possibility of encountering hard dolerite rock under the Firth; outcrops such as Beamer Rock demonstrate that there are dolerite intrusions in the area. It is likely that high groundwater pressures would be encountered in the river sediments. Figure B19 shows an indicative geotechnical cross section.

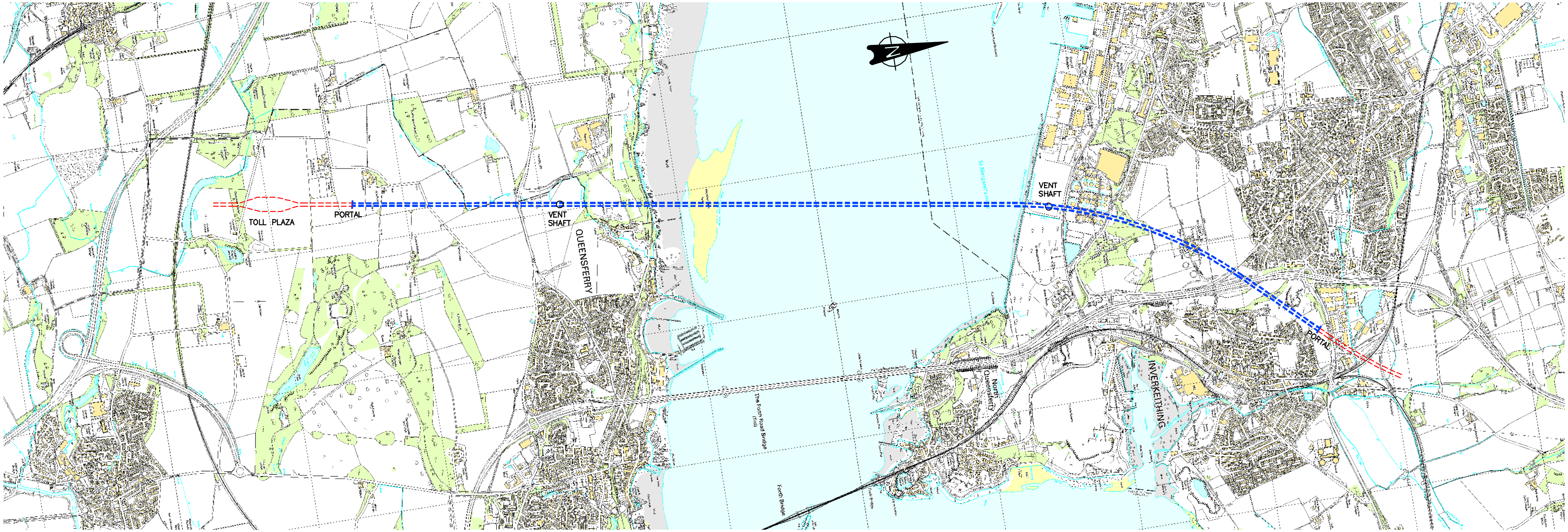
Sandstone, shale and coal are generally suitable materials for mining, as this technique is suited to competent rock that can support itself until the excavation pass is complete and the lining is installed but is also not too hard so that it can be readily excavated by roadheader or similar means. Where harder rock, for example, dolerite, is encountered, drill and blast techniques may be required.

Borehole logs close to the alignment of the tunnel on both banks of the Forth suggest that the rockhead is reasonably shallow. The topography of the area reinforces this with steep cliff-like shorelines rising from the water. Mining generally requires a minimum of five to ten metres of rock cover depending on the quality of the rock and amount of overburden. The tunnel is generally deep enough with the possible exception of the portals where the tunnel approaches the surface, so that the rock cover should be readily achieved.

Due to its suitability for the anticipated conditions and its lower relative cost, mining is recommended as a suitable method for tunnel excavation on both sides of the Forth based on the limited geotechnical data available. However, it should be noted that this needs to be confirmed by a detailed site investigation to confirm the type, quality, and depth of rock along the proposed alignment.

Cost Estimates

The cost estimates for the construction of the Corridor D Tunnel were derived by using the detailed cost estimate of Option C as a basis for calculating a unit rate per metre of tunnel length for each tunnelling technique. The unit rate was then calculated by the length of tunnel to derive the overall tunnel construction costs. Section 5.4 of this report discusses the approach used in more detail. A summary of the costs are contained in Section 5.10 of the Volume 1: Main Report.



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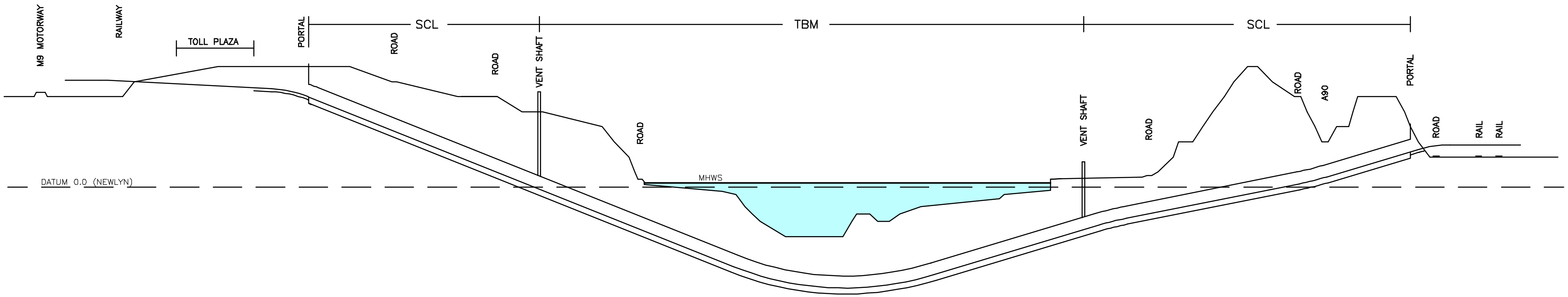


PROFILE VERTICAL / HORIZONTAL DISTORTION 10:1

CORRIDOR D TUNNEL

FIGURE B20

B7.3 Corridor E Tunnel

Introduction

The proposed tunnel on Corridor E is approximately 7.3 kilometres long. The alignment is shown on Drawing Number T/BE1/01. The southern portal and toll plaza (if required) are located to the south of the A90 and to the west of the Dalmeny oil storage depot. The proposal involves locating the possible toll plaza in an open cutting that transitions to a retained cut approach ramp and a short cut and cover tunnel from Chainage 2200 to 2700 under the M9 spur extension, and proposed link roads, where the available cover is insufficient for a bored or mined tunnel. A mined SCL tunnel is proposed until Chainage 3900, where a ventilation shaft is located south of the B924 near Dalmeny Park. From there, a TBM tunnel is proposed until Chainage 5100 at the edge of the deep channel where it interfaces with an immersed tube tunnel. The immersed tube tunnel runs for approximately 1.7 kilometres to the northern side of the deep channel. A TBM is again proposed from Chainage 6800 to 8400 where the second ventilation shaft is proposed to the north of Inverkeithing Bay. From here, a mined SCL tunnel is envisaged to the portal at Chainage 9500 immediately north of the A921.

Constructability Issues

Construction of the immersed tube section of the tunnel provides a number of challenges. A suitable casting basin must be found for construction of the units. A dry dock is located at the Rosyth Dockyard. However, should permission not be granted for this dock during construction a possible alternative casting basin has been identified immediately west of the dockyard, but it would need extensive modifications to be used as a suitable dry dock.

It is likely that the alignment would encounter hard dolerite rock. Outcrops in the area such as Inch Garvie demonstrate that there are dolerite intrusions in the vicinity of the tunnel corridor. This is supported by study of the Admiralty charts for the channel in this area, as there appears to be a number of submerged intrusions. These are likely to be caused by strong tidal flow through the area producing different erosion and deposition characteristics than the shallower areas of the Forth west of the existing bridges. The final alignment would need to avoid these areas of hard rock as much as possible. Where this is not possible, the rock would need to be dredged by drill and blast techniques to create the required bed profile for the immersed tube. If dolerite was encountered along the TBM route, it is likely that intervention from the surface would be required by sinking a caisson or cofferdam from the surface so that removal of the dolerite could be done by mining or other means in a dry environment.

The interface between the immersed tube and the TBM is located at the edge of the deep channel. The interface is likely to require the construction of a large caisson or cofferdam to provide a dry working area for the interface. On the southern side, the side walls of the channel rise quite sharply so it may be assumed that the rockhead profile closely follows the side of the deep channel. In this instance, construction of the cofferdam may incorporate the side wall of the channel with some trimming and excavation of rock to create a suitable vertical face for the TBM breakthrough. A soft eye would be constructed in the outer wall of the cofferdam which is broken through once the immersed tube units have been placed and sealed against the cofferdam. On the northern side, the walls of the deep channel are not as steep, indicating the possibility of softer material. A fully enclosed cofferdam may be required with soft eyes on both sides for breakthrough by the TBM on one side and through to the attached immersed unit on the other. Given that the TBM needs approximately two diameters of cover above the crown of the tunnel, a significant amount of dredging would be required to obtain the required depth for the immersed units and for the cofferdam itself.

A special cast in situ connection unit needs to be cast in the cofferdam to transition the tunnel from the circular cross section of the TBM to the rectangular shape of the immersed tube units. This affects both the traffic envelopes and the location of all services within the unit including but not limited to the fresh air and exhaust ducts. These special units are complex and generally expensive to construct.

On the south side, there have been significant mine workings in the area of the proposed tunnel portal and toll plaza (if required). The area has been recently grouted to a depth of approximately 60 metres prior to the construction of the M9 spur extension.

The BP Kinneil to Dalmeny oil pipeline runs directly adjacent to the proposed southern portal and would almost certainly need to be diverted prior to construction. The Dalmeny to Hound Point export pipelines cross the proposed alignment approximately 750 metres north of the portal. The tunnel is approximately 25 metres underground in competent rock at the crossover point and, provided vibration and settlement are controlled, construction of the tunnel should not adversely affect the pipeline in this location. However, the pipelines cross the tunnel alignment again and run parallel to it close to the proposed ventilation shaft located south of Dalmeny Park and the B924. The location of the ventilation shaft needs to be carefully chosen, but, given that the site is relatively large, it is envisaged that a suitable location for the shaft can be accommodated without disruption of the pipeline.

At the southern portal, a short section of cut and cover tunnel is required as there is insufficient cover for a bored or mined tunnel. This means that the M9 spur extension that is currently under construction needs to be temporarily diverted in order to construct the approach ramps and tunnel portal. Based upon the limited geotechnical information available, it is envisaged that a roadheader could be used from both portals as far as the shorelines. This offers the opportunity of concurrent construction of all sections of the tunnel if other worksites are set up at the ventilation shaft locations and used as reception and launch chambers for TBMs, while fabrication, dredging and placement of the immersed tube tunnel can occur independently.

Construction and Ventilation Shaft Sites

Potential construction sites have been identified and are shown on Drawing Number T/GE1/01. The sites are at the tunnel portal and shaft locations because permanent above ground structures need to be constructed there.

The A921 forms the southern boundary of the northern portal construction site. The northern perimeter of the site follows the line of the railway. The topography of the land is reasonably level. Streams run through the area at various points and these need to be piped under ground or diverted prior to construction. Access to the site is from the A921 which has connections to all routes. The use of the existing railway line to transport heavy tunnelling equipment to the site is also a possibility.

The site identified as a possible location for the construction of a shaft on the northern bank is a steeply sloped L shaped site. This construction site is not ideal. However, due to ventilation requirements and environmental constraints no alternative sites are practical.

The proposed construction site for the southern portal is the area bounded by the A90 to the north and the railway line to the east. It is a level greenfield site and is approximately 750 metres by 500 metres. Access to the M9 is available via the A8000. The BP Kinneil to Dalmeny oil pipeline runs across the site and would almost certainly need to be diverted. A stream also runs through the proposed site and this may also need to be diverted or piped underground.

For the immersed tube tunnel an additional worksite is required for casting the tunnel units. Rosyth Dockyard would be a suitable fabrication site for the units as the existing dry dock would only require minor modification. However, it is unlikely that permission would be granted for use of this dock during construction. A possible alternative casting basin has been identified immediately west of the dockyard, but it would need extensive modifications to be used as a suitable casting basin. The Fife Structure Plan 2002 (Approved) and 2006 to 2026 (under consideration by Scottish Ministers) has outlined plans for this site. However, it also states that if the land is required for the construction and operation of a replacement Forth Crossing, then it would be safeguarded. This site is 330 metres by 660 metres and would provide sufficient space for the construction of the units which are up to 40 metres wide and 120 metres in length.

Horizontal and Vertical Alignments

The horizontal alignment of the tunnel is constrained by a number of factors, including, but not limited to, the location of the portals (and possible toll plaza on the south side) and the required connections to the road network and their performance against the Forth Replacement Crossing Study. It is also necessary to maintain minimum radii on horizontal curves in order to satisfy stopping sight distances. The chosen alignment also considered the requirement for ventilation shafts at the shorelines and looked to avoid any environmentally sensitive areas. It also considered the likelihood of these shafts being used as reception and launching chambers for TBMs.

Due to the depth of the Firth channel along this corridor and given the minimum cover requirement of twice the TBM diameter, the gradient of a fully bored TBM tunnel at this location would have been too steep to effectively connect with the road network. An immersed tube tunnel requires only approximately five metres of cover at the bed of the Firth.

The gradient that has been achieved on the southern approach to the immersed tube is 3.3 per cent, which is just over the recommended maximum. The increase in tunnel gradient above three per cent may require additional safety measures in accordance with the EU Road Tunnel Safety Regulations 2007 Consultation Draft. Further refinement of the alignment at detail design stage should ensure that the gradient stays close to three per cent.

On the north side of the Firth, the vertical alignment remains at approximately three per cent to the portal. For a bored TBM tunnel, one diameter of cover is required at the portals. By using a mined SCL tunnel, this may be reduced but this is dependent on the quality of the rock above the crown of the tunnel. It is anticipated that a short cut and cover tunnel would need to be constructed until sufficient rock cover is achieved. This would not affect the vertical alignment of the tunnel.

Road Network Connections

Details of the road network connections for Corridor E Tunnel are covered in Section 4 of Volume 1 Main Report.

Geotechnical Conditions

Investigation of the limited available geotechnical data indicates that the tunnel must negotiate shales, sandstones and coal measures on both banks of the Forth. It is likely to encounter soft alluvial sediments and glacial deposits under the Firth. There is a significant possibility of encountering hard dolerite rock throughout the alignment. Outcrops such as Inch Garvie demonstrate that there are dolerite intrusions in the area. There is very little information available regarding the rockhead contours under the Forth so an indicative geotechnical cross section has been developed with a conjectured rockhead profile. This is shown in Figure B21.

It is likely that high groundwater pressures would be encountered in the river sediments. There has been significant mine workings in the area of the proposed toll plaza and southern portal. The area has been recently grouted to a depth of approximately 60 metres prior to the construction of the M9 spur extension. Figure B22 shows an indicative geotechnical cross section.

Sandstone, shale, and coal are generally suitable materials for mining, as this technique is suited to competent rock that can support itself until the excavation pass is complete and the lining is installed but is also not too hard so that it can be readily excavated by roadheader or similar means. Where harder rock, for example, dolerite, is encountered, drill and blast techniques may be required.

Borehole logs close to the alignment of the tunnel on both banks of the Forth suggest that the rockhead is reasonably shallow. The topography of the area reinforces this with steep cliff-like shorelines rising from the water. Mining generally requires a minimum of five to ten metres of rock cover depending on the quality of the rock and amount of overburden, so with the possible exception of the portals, where the tunnel approaches the surface, this cover should be readily achieved.

Due to its suitability for the anticipated conditions and its lower relative cost, mining is recommended as a suitable method for tunnel excavation on both sides of the Forth based on the limited geotechnical data available. However, it should be noted that this needs to be confirmed by a detailed site investigation to confirm the type, quality and depth of rock along the proposed alignment.

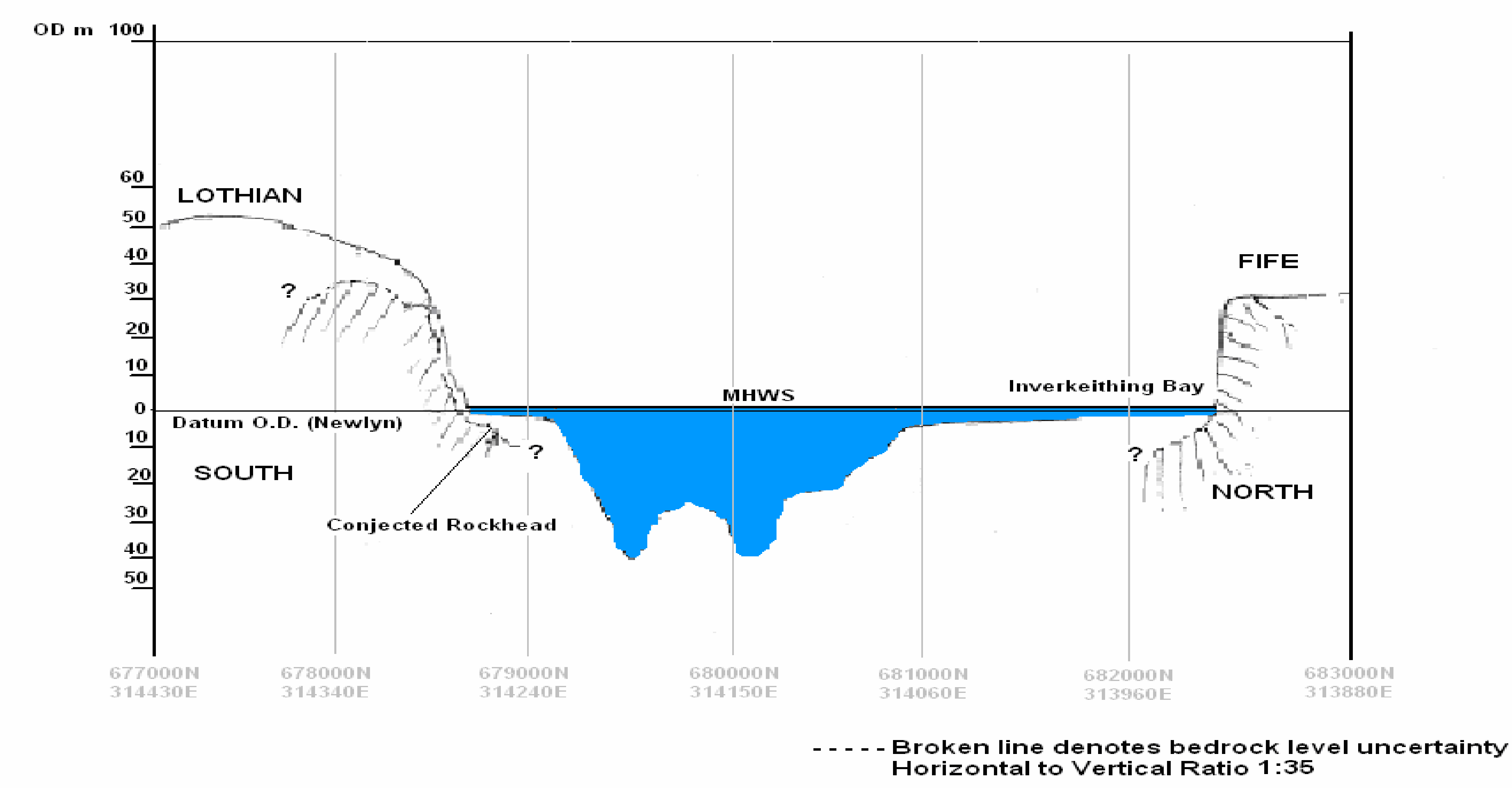
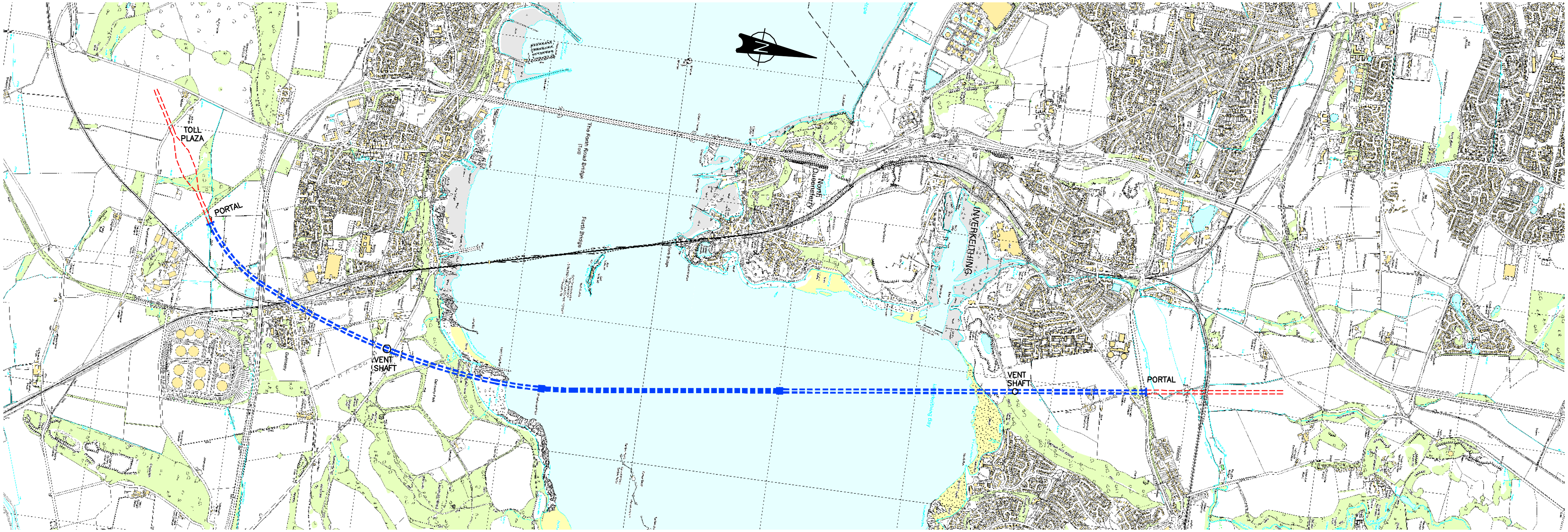


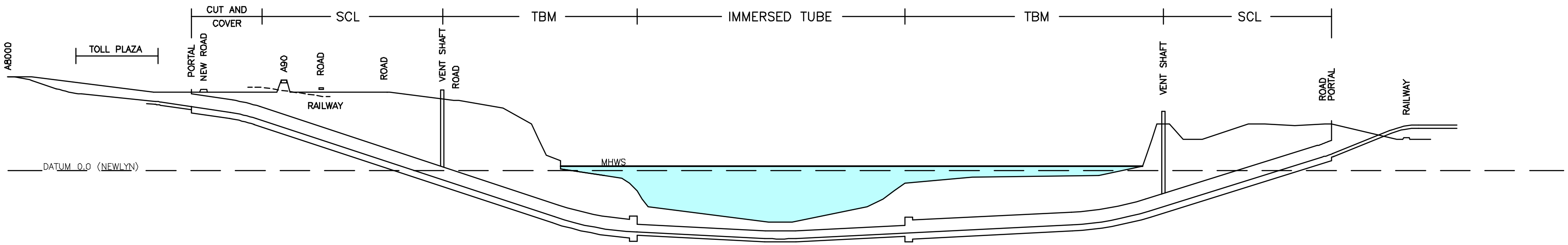
Figure B21 – Corridor E - Indicative Geological Cross Section

Cost Estimates

The cost estimates for the construction of the Corridor E Tunnel was derived by using the detailed cost estimate of Option C as a basis for calculating a unit cost per metre of tunnel length for the SCL, TBM and C&C tunnelling techniques. The cost of the immersed tube section was estimated by comparing the all-in costs for similar project carried out both in the UK and abroad. Section 5.4 of this report discusses the approach used in more detail. A summary of the costs are contained in Section 5.10 of the Volume 1: Main Report.



PLAN



PROFILES VERTICAL / HORIZONTAL DISTORTION 10:1

CORRIDOR E TUNNEL

FIGURE B22