# APPENDIX A - GENERAL DESIGN AND CONSTRUCTION ISSUES

## A1 INTRODUCTION

This Appendix presents the general and specific issues which influence the design of a replacement crossing.

For any possible bridge crossing, the most feasible options would be either a suspension bridge or a cable stayed bridge. No other bridge option would meet the span and navigation clearance requirements of the Forth. For a potential tunnel crossing, options include a bored tunnel utilising a tunnel boring machine (TBM), immersed tube, mined tunnel and cut and cover tunnel.

Before considering the design and construction issues relating to bridges and tunnels, some Health and Safety aspects associated with Design, Construction, Operation and Maintenance are examined.

## A2 HEALTH AND SAFETY

Health and Safety is of paramount importance to all construction projects and for a project of national importance it will be particularly under public scrutiny. The construction of a bridge or tunnel crossing will involve a workforce of several hundred personnel and their Health and Safety together with that of the general public where impacted will be of prime importance.

Health and safety can be considered in 3 main stages

1. Design and Planning

Health and Safety starts at the very beginning of all construction projects during the planning and design phases. Legislation under the Construction,(Design and Management) Regulations of 2006 leads to well documented approach to safety in design and co-ordination of designers. A risk register is produced highlighting all risks and proposed mitigation measures.

One of the main purposes of CDM is to identify major risks and the determination of mitigation factors to eliminate or reduce that risk to an acceptable level. In this way, for example, it is highly likely that the design of the south anchorage will employ a gravity anchorage rather than a tunnelled anchorage to minimise excavation in ground known to contain methane.

2. Construction

All construction work will be carried out in accordance with all relevant Standards, Codes of Practice and all current legislation covering such issues as lifting equipment, working at height.

For construction of suspension and cable stayed bridges the following major risks apply.

| Bridge Construction Activity | Bridge Construction Risk |
|---|---|
| Foundation and Anchorage Construction | Working over or alongside water<br><br>Excavation in Ground |
| Tower and other pier construction | Working at Height<br><br>Working over or alongside water<br><br>Instability of Permanent Structure during construction<br><br>Instability of Temporary Works |
| Suspension or Cable Stay Erection | Working at Height<br><br>Working over or alongside water<br><br>Instability of Temporary Works |
| Deck erection | Working at Height<br><br>Working over or alongside water<br><br>Instability of Permanent Structure during construction<br><br>Instability of Temporary Works |
| Construction of Approach Roads and Viaducts | Utility Disruption<br><br>Working alongside live traffic<br><br>Instability of Permanent Structure during construction<br><br>Instability of Temporary Works<br><br>Working at Height |

The safety mitigation measures for the major risks are set out below

| Bridge Construction Risk | Safety Mitigation Measure |
|---|---|
| Working at Height | Risk assessments, method statements to be developed and approved; safe systems of work to be adopted; protection of public assured by safe systems of work and barriers if deemed necessary through risk assessment; use of specialist personnel, personal protective equipment |
| Working over or alongside water | Risk assessments, method statements to be developed and approved; safe systems of work to be adopted; safety boats to be used; protection of public assured by safe systems of work and barriers if deemed necessary through risk assessment; for foundation work caissons to be used |
| Instability of Permanent Structure during construction | Identification and mitigation of potentially unstable conditions identified during the design phase and noted in Contract documents; mitigation measures to be implemented by the Contractor; risk assessments and method statements to be developed and approved; check of temporary construction loads on permanent structure |
| Instability of Temporary Works | Temporary works to be designed, tested and independently checked by competent designers; temporary works to be installed by competent contractor in accordance with the design and approved method statements |
| Excavation in Ground | Adequate advance site investigation to determine ground parameters; excavations to be propped as necessary |
| Utility Disruption | Gather documentation of utilities in the vicinity of the works; adequately protect or divert utilities prior to the works |

| | |
|---|---|
| Working alongside live traffic | Establishment of safe working areas, risk assessments and method statements to be developed and approved, |

The main Health and Safety risks associated with tunnel construction relate to collapse of the tunnel shaft and lack of ventilation. Other risks such as those relating to the approach roads are similar to a bridge.

| Tunnel Construction Risk | Safety Mitigation Measure |
|---|---|
| Instability of tunnel shaft | Provision of watertight segmental lining behind the boring machine |
| Lack of Ventilation | Adequate temporary ventilation to be provided in the shaft at all times until the temporary ventilation system has been installed |

3. Operation and Maintenance

At the completion of construction, in accordance with the CDM regulations, the Contractor will need to provide a Safety File and an Operation Manual for the bridge or tunnel. The purpose of the Health and Safety File is to provide information to protect the health and safety of those involved in future construction work on the structure which will include alteration, dismantling and demolition work.

Safe methods of maintaining the structure will be developed to maintain safety of all bridge users as well as the maintenance team. For details of maintenance of replacement bridge crossings refer to section 5.3.14. .

## A3 SUSPENSION BRIDGES

Suspension bridges are technically feasible within the Forth Firth and have the advantage that they can provide large spans of up to 2000m. This has a clear benefit of providing adequate navigation clearance and minimises foundations for piers in the Firth of Forth. However, suspension bridges of this span are highly complex structures with a high cost penalty and are at the forefront of technology. The risks associated with the cable erection are high and could lead to potential delays in the construction programme. Clearly, the shorter the span, the lower complexity, cost and programme certainty can be achieved. The Forth Road Bridge is a suspension bridge with a maximum span of 1006m and the preferred option for the crossing during the Setting Forth study was a suspension bridge with a maximum span of 1375m.

The maximum span suspension bridge achieved to date is the Akashi Kaikyo Bridge in Japan with a maximum span of 1991m. The main towers, which are 298m above water level, are 142m higher than those of the Forth Road Bridge. In the following sections it will be shown that bridges with spans of this magnitude may be necessary to cross the Firth of Forth within some of the corridors under consideration.

**Figure: A.1 Akashi Kaikyo Bridge**

Approach viaducts and link roads will be required to connect any new bridge (or tunnel) to the associated transport networks. For more details refer to section 5.3.9 of this report.

The advantages of suspension bridges compared to cable stayed bridges are set out below:

- the long spans provide maximum clearance for navigation channels;
- the design minimises the number of piers and foundations in the Firth;
- by reducing the number of river piers a suspension bridge potentially reduces the environmental impact and blockage of the Firth that would be associated with foundation construction; and
- the longer span possible means that foundations of a suspension bridge can be founded in relatively shallow water, so reducing the construction and cost risks of working in deeper water;

The disadvantages of suspension bridges compared to cable stayed bridges are;

- construction risks associated with erection of the main cable and deck in this exposed environment of the Forth. However, significant construction risks are also associated with the deck erection of cable stayed bridges.

- potentially increased risk of methane on the south landfall. During construction of the Forth Road Bridge south anchorage, methane was detected in the anchorages. Current health and safety standards would lead the design to a gravity anchor solution which would minimise any excavation; and

- a suspension bridge has a slightly longer construction programme compared to a cable stayed bridge. For the bridge envisaged in the mid 1990s as part of the construction programme was expected to be 5.5 to 6 years. A cable stayed bridge would take around six months less to construct. Longer suspension bridges may require construction periods of seven years or so.

In the following section the design considerations affecting a suspension bridge are presented.

### A3.1 Bridge Cross Section/ Highway Clearances

As explained in Chapter Four, it is proposed to assume that a dual two lane carriageway plus hard shoulder on each of the crossings modelled for this assessment. The bridge options appraised would incorporate dual 7.3m wide two lane carriageways with standard 3.3m wide hard shoulders. However, it should be noted that in Setting Forth, this was reduced to 2.6m wide hard shoulders. A 2.1m wide central reserve would be provided between the two carriageways with safety fence at the edge of the carriageway. High containment safety fences would be provided at the back of the hard-shoulder to protect inspection and maintenance personnel working outside the carriageway boundary. Outside the safety fences, maintenance access ways would be provided to allow routine inspection and maintenance work to be carried out without the need for carriageway restrictions or hard shoulder closures. The maintenance access ways would be at least 3.6m wide except at obstructions such as communication cabinets, lighting columns, etc. where a minimum width of 2.6m would be provided. The overall width of the deck would be approximately 36.5m. The depth of the deck would be some 5m.

### A3.2 Typical Construction Sequence

The construction of a suspension bridge follows a generally linear programme, with little opportunity for concurrent working. The exception to this is that more than one tower or foundation can be constructed at the same time if the resources, particularly specialist plant, are available. The broad sequence of activities is as follows:

- construct foundations and anchorages;

- construct towers and backspan piers;

- install main suspension cables;

- erect cable hangers and deck units; and

- install finishes (road surfacing, bridge deck furniture, communications, etc.).

## A3.3 Foundations and Anchorages

It is anticipated that most foundations sited within the Firth would be required to bear directly on bedrock to satisfy design and performance criteria for the structure. The main bridge piers and foundation would be designed to resist ship impact. For lesser loaded structures such as the approach viaduct piers and possibly also the cable anchor blocks, foundations may be founded on the stiff cohesive glacial deposits or the glacial sands and gravels. However, it is more likely that these would be piled.

A range of construction techniques might be employed within the marine environment of the Forth. Methods would depend on the respective loadings, movement and overturning criteria, ship impact and the specific ground conditions occurring at any given location.

Possible methods of constructing foundations are:

1 Artificial Island. These could be employed in shallow water to allow working platforms for diaphragm walling and caisson construction, these forms of construction of water tight structures to allow the water to be pumped out and the pier foundations to be constructed;

2 Piling involving bored, driven or drilled cylinders;

3 Cofferdams. These could be employed over most of the potential foundation areas to gain access for caisson or directly bearing foundations. They can be flexible in shape and depth; and

4 Caissons. Box caissons are open at the top and closed at the bottom and can be placed directly onto a prepared foundation. Open caissons are open both ends allowing materials to be removed by grab and/or suction.

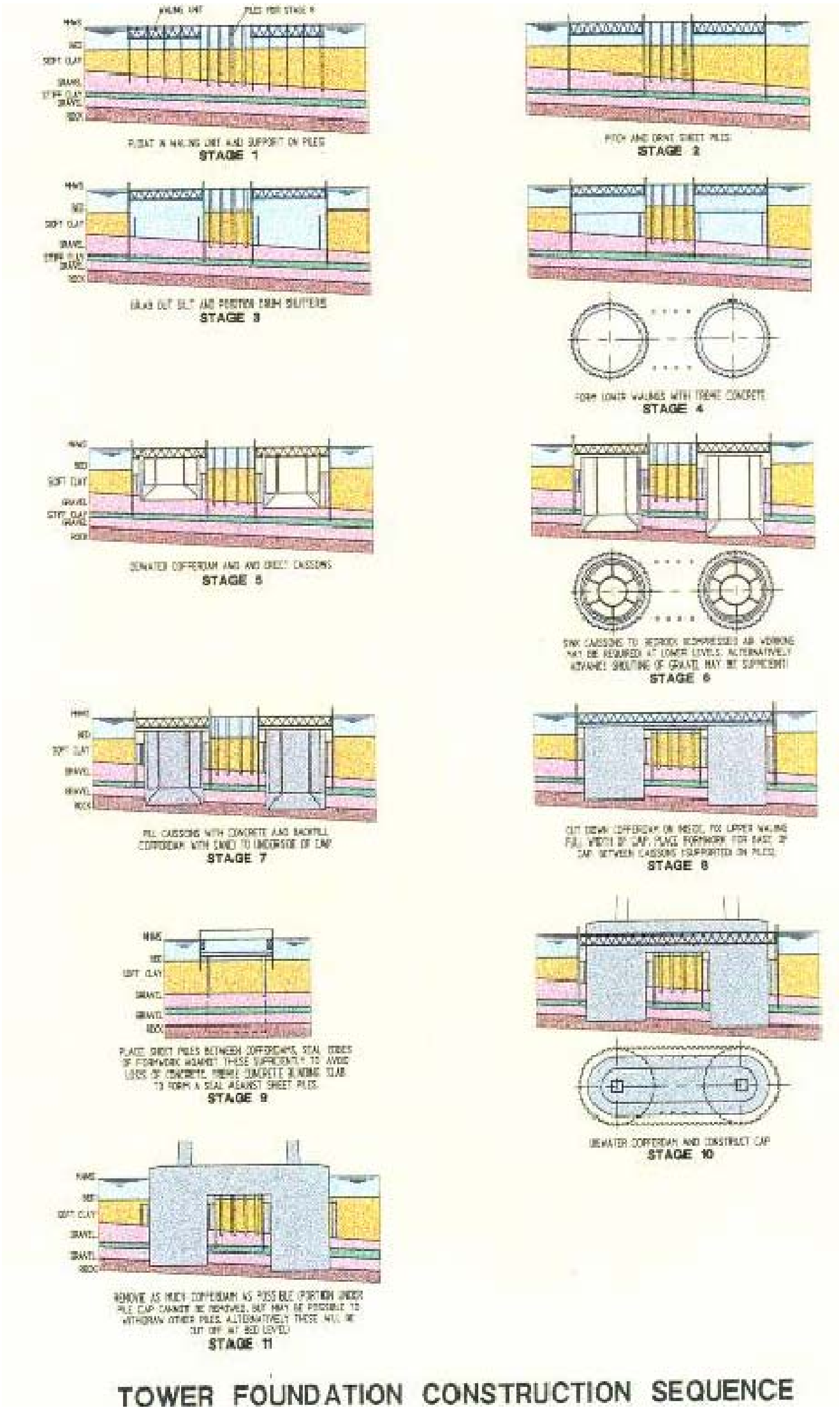
Of these methods, it is most likely that the construction of the main tower foundations typically involves caissons.

The most critical issue for a typical construction sequence for main tower foundations is shown in Figure A.2.

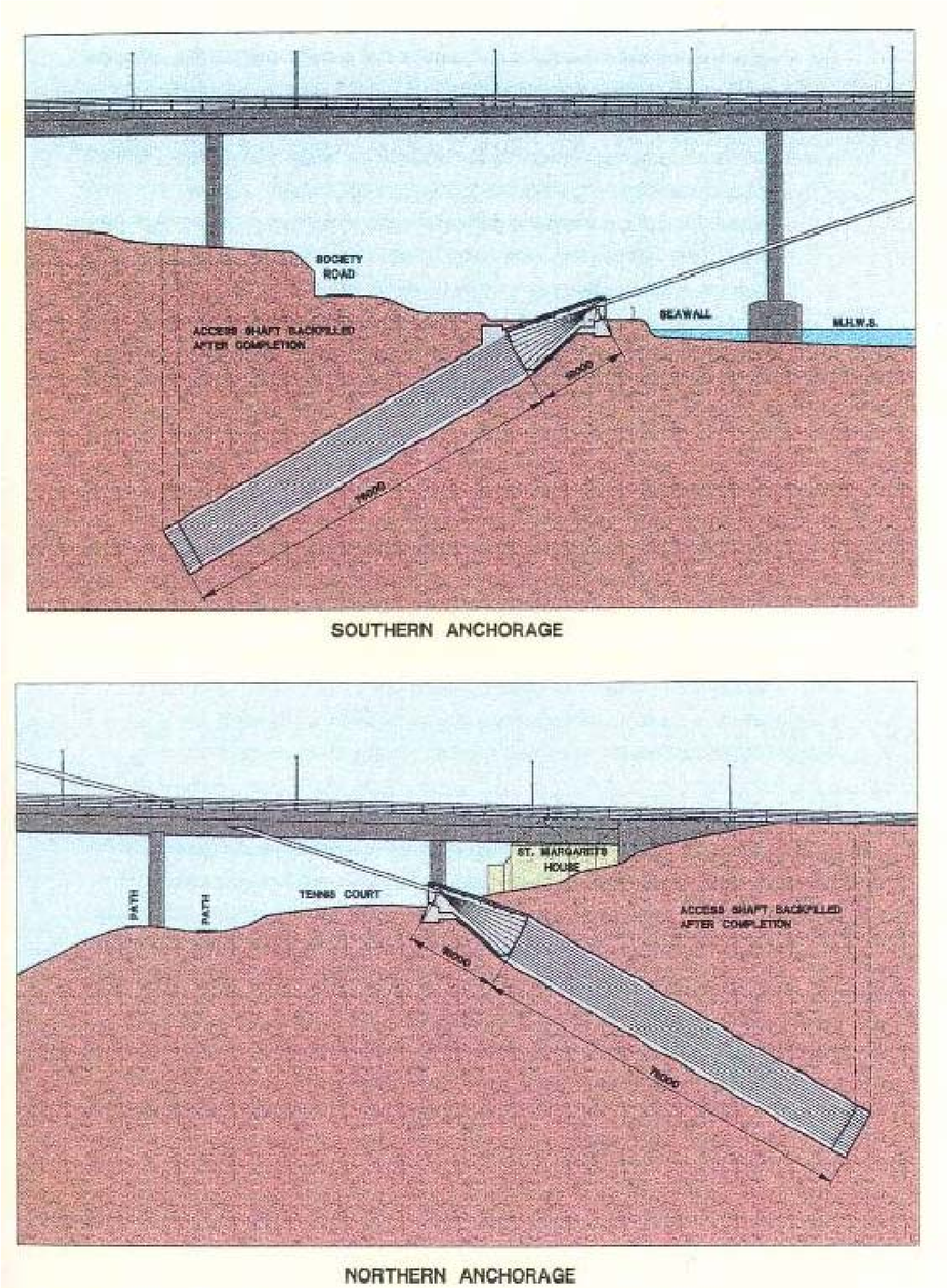
Cable anchorages are required to resist the tension from the main cables supporting the deck. Anchorages can be achieved by constructing rock tunnels and securing the cables within these tunnels, but only if competent rock is present. If rock of suitable quality is not present, a gravity anchorage system could be employed. In such cases, the tension of the cables is resisted by the mass of the anchorage itself. This is illustrated in Figure A.3.

During construction of the south anchorages for the Forth Road Bridge an explosion occurred. This was believed to be due to a sudden and unexpected release of methane gas into the workings. This is an extremely important design consideration which must be incorporated into the design and construction of any new suspension bridge. The use of gravity anchorages would reduce excavation and hence minimise construction risks. The gravity anchors resist the tension force in the cable through its own weight and resistance to sliding. The gravity anchor will therefore be large and quite likely to be visually intrusive.

## Figure A.2 Tower Foundation Construction Sequence



## Figure A.3 Construction of Anchorages



## A3.4 Towers

The main towers for a suspension bridge can be constructed using reinforced concrete or steel. For the Setting Forth option, it was proposed to construct the towers using reinforced concrete. This decision was made primarily following analysis of the towers when subjected to fire fire following a ship impact. The results of the analysis indicated that the fire could be of sufficient magnitude to cause significant damage to steel towers. It was therefore decided that concrete towers should be used for increased fire resistance.

In addition to this consideration, recent experience of the protection required to paint the steel towers of the existing Bridge adds additional further support to the preference to use concrete towers for possible bridge crossings. In addition, painting is known to be time consuming and expensive and it requires enclosure and other works to protect traffic and the environment.

The proposed legs of the bridge for the Setting Forth option were hollow and were approximately 7.5m by 4m. The crossbeams of the towers were concrete and either cast in situ reinforced concrete or pre-cast at one of the construction sites, lifted into place and stressed to the tower legs. Once the concrete construction was complete, large steel saddles would be placed on top of the towers to carry the main suspension cables.

The main risks associated with tower construction in this type of environment relate to the weather conditions and its affect on the programme and cost.

## A3.5 Backspan Piers

Backspan piers provide support for the main cables and the back spans. Typical construction techniques would employ conventional reinforced concrete foundation and substructure construction methods using a spread footing or short piles with a pile cap.

## A3.6 Suspension Cables

Main suspension cables are typically constructed using one of the two following methods.

- Aerial spun cables, the cables are erected by running individual wires between the anchorages and over the main and backspan tower saddles using spinning wheels. The individual wires are subsequently compacted together and wrapped to prevent corrosion. In this operation an aerial ropeway and catwalk working platform would be provided crossing from one shore to the other and passing over the saddles at the top of the towers. This is a high risk activity and can typically take three to four months to complete. It is on the critical path and therefore any delays would directly affect the overall programme.
    - High strength wire would be delivered to an unreeling shop at one end of the aerial ropeway where it is prepared for installation. A number of wires (typically four) can be installed at the same time and these are carried along

the aerial ropeway on “spinning wheels” to the far anchorage where they can be secured.

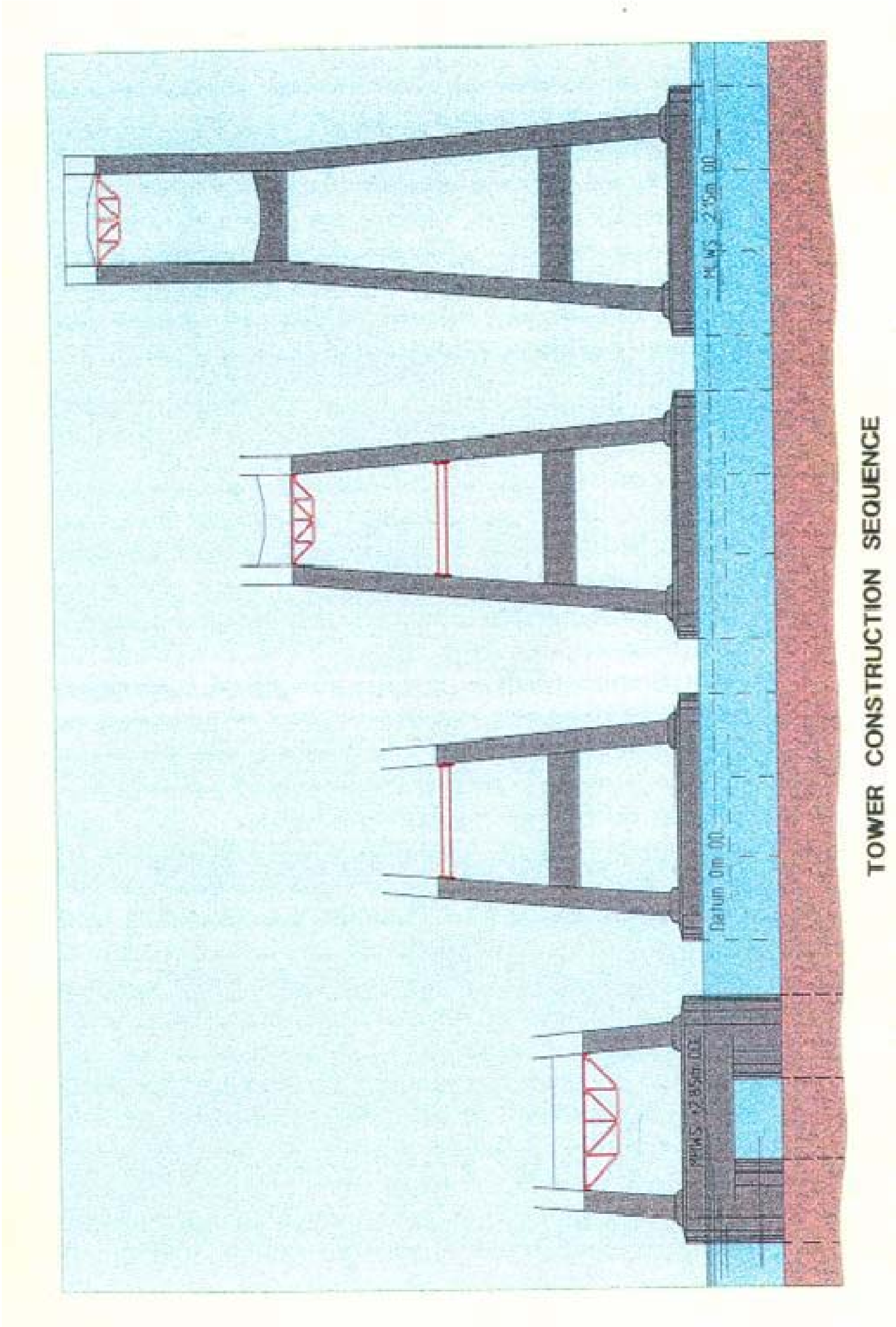
  - Previously in the Setting Forth Study, the proposed suspension cable had an overall diameter of 860mm and comprised of approximately 23,200 separate 5mm diameter wires. Cable spinning operations can be sensitive to adverse weather conditions, particularly high winds, and are likely to occupy some 16 months of the construction programme. Cable spinning is illustrated in Figure A.5.

  - Once the main cable is in place, the individual wires would be compacted together to form a tight group and secured together by cable bands. A further layer, comprising a surface coating and a wrapping of galvanised wire is then applied around the cable to act as a protective covering. This covering is painted to offer further protection.

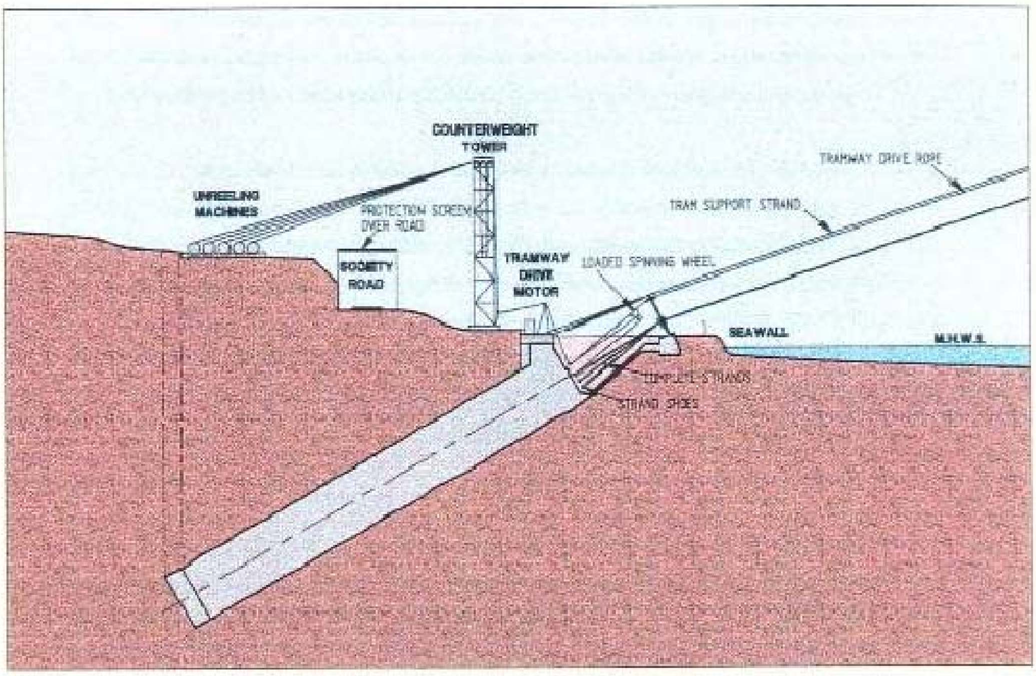
  - Employing lessons learnt from the Forth Road Bridge and examples of more recent suspension bridges, dehumidification systems would be installed within the cables during construction and used throughout the lifetime of the bridge to minimise corrosion to the cables.

- Preformed parallel wire strands (PPWS). The anchorages for the PPWS are likely to be larger and hence more costly than for aerially spun cables. However, this method is slightly less prone to weather and poor visibility risks than aerially spun cables. The expected quality of a PPWS cable is generally higher due to reduced wire and galvanising damage during erection.

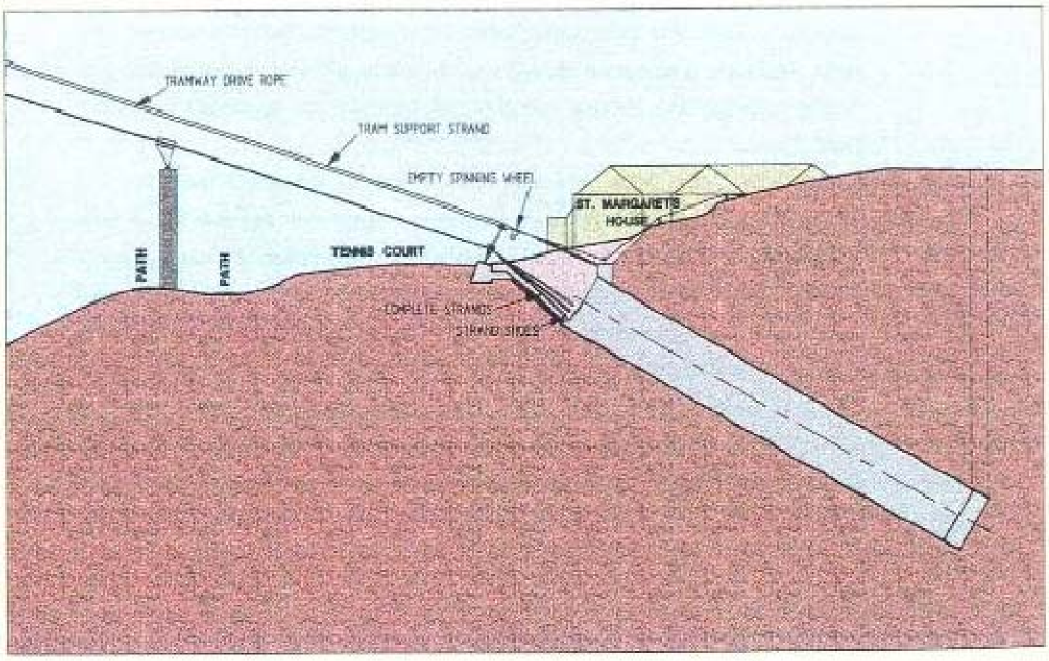
## Figure A.4 Tower Construction Sequence



## Figure A.5 Installation of Cable Spinning at Anchorages




SOUTHERN ANCHORAGE (CABLE SPINNING)

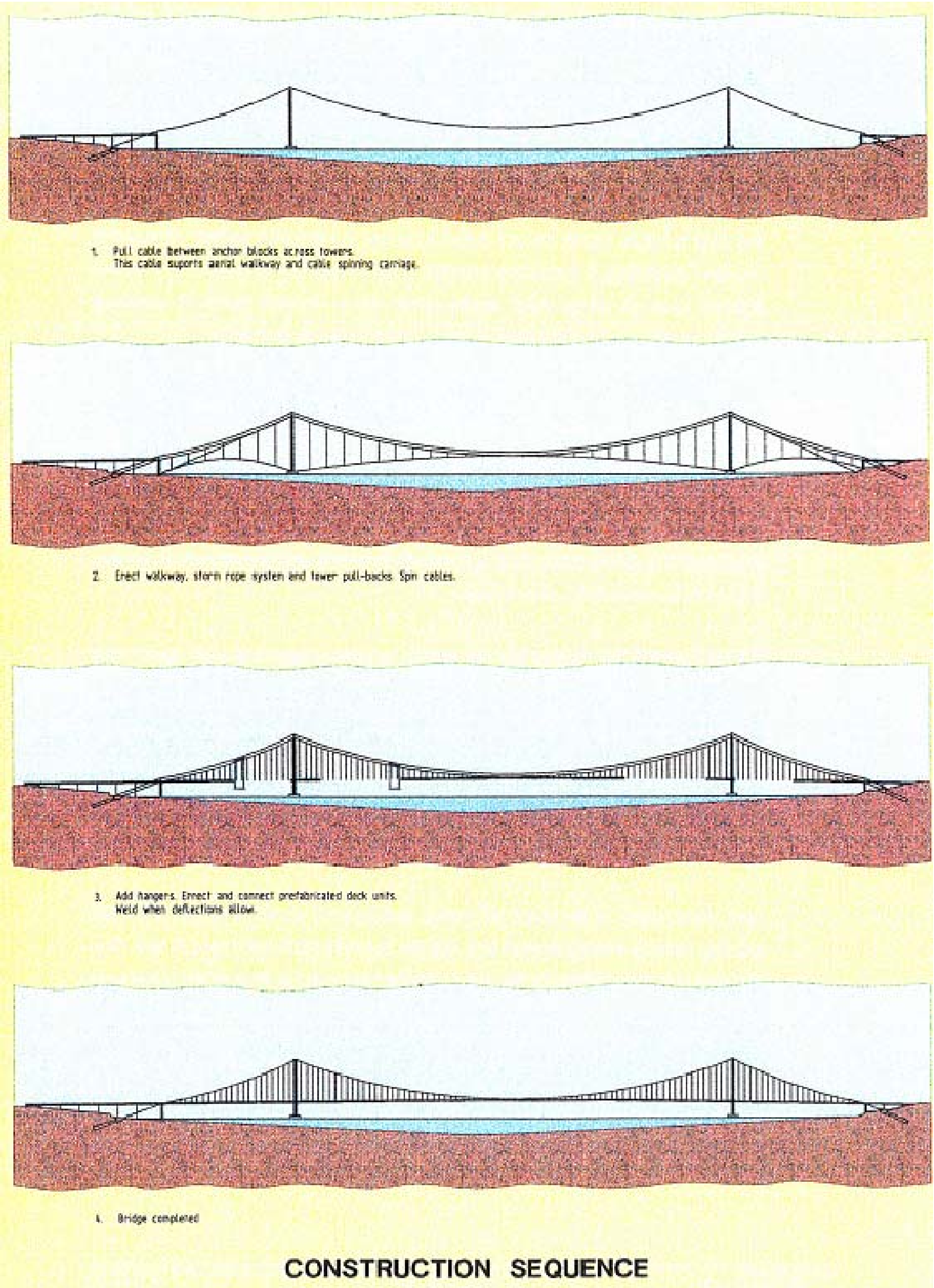



NORTHERN ANCHORAGE (CABLE SPINNING)

### A3.7 Bridge Deck

After completion of the suspension cables, steel box girder units could then be erected. The actual construction method would depend on the availability of local construction sites, specialist plant or the location of the contractor's own fabrication facilities. A typical sequence is illustrated in Figure A.6.

**Figure A.6 Typical Suspension Bridge Construction Sequence**



The individual panels for the deck units would probably be manufactured in a steel fabricator's works and transported to a local construction site for assembly into units.

The completed units would be transferred to a barge and taken out to the deck erection front where they would be lifted into position by winches on purpose-made cradles travelling along the main cables. Once in position the deck units would be attached to the cable hangers which would be installed ahead of the deck erection front.

Welding of the erected deck units to their neighbours would continue behind the erection front although a lag between the operations would need to be allowed to ensure that the welded joints were not overstressed during the erection of further units.

There is a likely requirement for the dehumidification of the steel box deck to assist the protection of the internal steel areas. Fixed lighting and power supplies would be incorporated in the box section to assist with future maintenance.

### A3.8 Finishes

Once a bridge deck was substantially complete, the deck surfacing would be laid and the deck furniture and motorway communications equipment installed. The Setting Forth design proposed that the depth of surfacing would be 50mm. Experience from the existing Forth Road Bridge, where the equivalent depth is 38mm, has shown that it would be of benefit to increase the thickness to avoid risking damage to the underlying steel deck during re-surfacing.

### A3.9 Approach Viaducts

Approach viaducts and suitable connecting roads would be required to link any bridge to the associated transport networks. The construction of these elements would not be on the critical path. It is probable that they would be built in conjunction with elements of the main bridge to provide some continuity of work for the operatives. However, it may be considered advantageous to construct them fairly early in the overall programme to provide access to the deck of the main bridge.

For the Setting Forth option, the form of construction was be steel plate girders with composite concrete deck spanning a maximum of 100m. The construction of the deck for the Setting Forth crossing was to follow conventional procedures and it was likely that this would be done with the steel primary members being erected first and the concrete deck being cast in situ. Detailed erection methods for the steel primary members would depend on the access for and capacity of available craneage. It is probable that, due to the weight of the long span, and to keep the size of cranes down to a sensible size, intermediate temporary towers would be required with the members being erected in part span lengths and spliced together on site.

The span of the viaducts would need to be optimised during the design. Larger spans of 150 m can be achieved using steel box girders. This is a similar form of construction to the approach viaducts for the Forth Road Bridge. The advantage of increasing the spans would be to reduce the number of foundations and piers. A Contractor may elect to transport the large span sections close to the required position by water. However, due to the extensive sections of mudflats the sections would then need to be transferred from the navigable section to its final position.

The Contractor may alternatively elect to construct the approach viaducts by the balanced cantilever method in which precast prestressed concrete segments are lifted into place progressively, cantilevering from both sides of the viaduct piers. This method was used for the second Severn Crossing.

Another possible method of constructing the approach viaducts would be by launching. In this method, straight sections of viaduct could be pushed out from dry land over the tops of the piers as a continuous section. The span of the viaduct would need to be limited to approximately 60-75m if this form of construction was adopted. This option is advantageous as it limits the work to be carried out over the mudflats. The disadvantage would be that the number of piers and foundations within the Firth would increase with a resulting increase impact on the environmental.

### A3.10 Aerodynamic Performance

Aerodynamic stability of long suspension bridges is an extremely important consideration in their design and construction.  This issue was most famously illustrated in the example of the Tacoma Narrows Bridge which became unstable under relatively low wind speeds.  Should a bridge be the preferred solution for an additional or replacement crossing, models of suitable bridges would be tested in wind tunnel machines. The models would incorporate significant existing topographical features and adjacent structures if present such as the existing Road and Rail Bridges.  These tests would be used to determine how well any new bridge remains stable up to critical wind speeds.

In section A.3.12 below, the effects of wind shielding are discussed. The addition of wind shielding has a major effect on the aerodynamic stability of the bridge. During the course of the Setting Forth studies, it was found that the deck needed to be widened to retain aerodynamic stability for the structure.

As noted above the presence of adjacent structures would also affect the performance of any new bridge.  During the Setting Forth studies, options for constructing a new bridge adjacent to the Forth Road Bridge were investigated.  It was concluded that the Forth Road Bridge would need to be strengthened if a new bridge was constructed immediately adjacent to it as the proximity of the new structure increased turbulence around the existing bridge.  As noted in Appendix E this option was discarded.

### A3.11 Ship Collision on Piers

Bridge piers need to be designed to withstand the impact of errant marine vessels. The only limitation in marine settings is the water depth which limits the size of vessel which could reach the piers.  The main foundations for the Setting Forth option were designed for impact from a 33,000 deadweight tonne (DWT) oil tanker. This is the largest vessel that can be accommodated at Grangemouth.

The potential impact force of such vessels will have a major influence on the design of the foundations. For the corridors where the rock level is significantly below the water level, any ship impact forces would need to be transferred by the pile group.

### A3.12 Wind Shielding

The recommended design of the bridge produced during Setting Forth included wind shielding. This was to improve the availability of the crossing by providing a degree of protection to wind susceptible vehicles (WSVs) such as high-sided vehicles.

In the UK, wind shielding is provided on the whole length of the Second Severn Crossing.  This was a conscious decision to provide protection to traffic on this strategic route, which suffered closures of the first Severn crossing during periods of high winds.

The addition of wind shielding increases the wind loading on the bridge and, more importantly, reduces the potential aerodynamic stability of the bridge.  Wind tunnel tests carried out for the Second Severn Crossing and for Setting Forth were used in the design of the Setting Forth options and it was found necessary to increase the deck width to ensure aerodynamic stability.

The study into wind shielding was carried out during the earlier stages of the Setting Forth study period, when a number of different bridge options were being pursued. The preliminary highway cross section accommodated a dual two lane carriageway with 3.3m wide hard shoulders. This gave an overall deck width of about 33 metres. To accommodate wind shielding, the deck width was increased to about 37 metres. The additional width was used to accommodate maintenance access outside the carriageway, leading to the bridge cross-section recommended.

### A3.13 Construction Programme

As part of the work carried out during the Setting Forth project, it was estimated that the construction time would be 5.5 to 6 years in duration. For comparison the construction duration for the world's 10 longest main spans is tabulated below.

**Table A.1 – World's Longest Suspension Bridges**

| Ranking | Name | Main Span (m) | Completion Date | Construction Duration (Years) |
|---|---|---|---|---|
| 1 | Akashi-Kaikyo, Japan | 1991 | 1998 | 10 |
| 2 | Great Belt Bridge, Denmark | 1624 | 1998 | 7 |
| 3 | Runyang, China | 1490 | 2005 | 5 |
| 4 | Humber, UK | 1410 | 1981 | 8 |
| 5 | Jiangyin, China | 1385 | 1999 | 5 |
| 6 | Tsing Ma, HK | 1377 | 1997 | 5 |

| | | | | |
|---|---|---|---|---|
| 7 | Verrazano Narrows, USA | 1298 | 1964 | 5 |
| 8 | Golden Gate,USA | 1280 | 1937 | 4 |
| 9 | High Coast, Sweden | 1210 | 1997 | 4 |
| 10 | Mackinac, USA | 1158 | 1957 | 2.5 |

It can be seen from the above table that the estimate is within the range of construction durations for completed long span suspension bridges.

In the main text the various crossing options for the Corridors A to E are introduced. For corridor D which is equivalent to the Setting Forth option, the likely duration of construction will be 5.5 to 6 years. For Corridors C and E with suspension bridge main spans up to 1850m, it is likely that the construction duration will be 7 to 7.5 years.

## A3.14 Future Maintenance

Introduction

As part of the CDM risk assessment required under Health and Safety legislation for the proposed replacement crossing it is necessary to consider the type of maintenance activities and risks which are inherent in a suspension bridge

In section A.3.1 above, the proposed bridge cross section was detailed in which the bridge would be provided with 2.6m wide hard shoulders. In addition, maintenance walkways with a minimum width of 2.6m would be provided outside the main suspension cables. High containment safety fences will be provided at the back of the hard shoulder to protect inspection and maintenance personnel working outside the carriageway boundary. In this way, inspection and maintenance work can be carried out without the need for carriageway restrictions or hard shoulder closures.

To carry out maintenance and painting of the box girder deck, a moveable maintenance gantry would be provided underneath the deck. Access to the internal surfaces of the box girder would be via manholes. Walkways would be provided within the box girder.

**General**

A structure of this nature would be subject to the standard Scottish Executive Highway Structures inspection regime. Typically this would involve routine two yearly inspections with principal inspections every six years. Special inspections such as internal inspection of the main cables would be arranged on the basis of risk assessment.

**Inspection findings from existing structures**

Making the assumption that any new crossing will use approximately the same technology and materials as the existing structures it is possible to predict the likely major maintenance issues.

**Routine paint protection**

- repair and recoating of aerofoil box type steel decks typically every 10 years - undertaken from the inspection gantry; access for maintenance of the internal surfaces would be via manholes into the boxes and a system of walkways located within the boxes.
- repair and recoating of the main cables is typically required every 10 years - requires special high level platforms; and
- repair and recoating of hangers is typically required every 10 years – requires abseil access.

**Bearings**

Typically cleaned and inspected every six years. Primary bearings would probably have a 120 year design life but maintenance experience suggests that a significant percentage would require replacement at a much earlier stage. It would be advisable to anticipate replacement of all bearings every 30 years. All bearings should be readily accessible for inspection with space and facility for replacement. Run-off from carriageways should not be allowed to reach bridge bearings. For replacement of bearings, adequate space shall be provided for installation of jacks and to allow safe working space together with adequate strong points on the bridge deck and substructure. The bearings should be designed to be removable and with minimum disruption to the bridge users. Access requirements should include access ladders, catwalks and landings with sufficient area and lighting for carrying out maintenance and repair work.

**Movement joints**

Due to the free movement lengths these are typically quite significant items, often with complex bespoke support structures. Typically these items would be thoroughly cleaned and inspected every six years. Existing maintenance experience suggests that these may need replacement several times during the life of a structure. It would be advisable to anticipate replacement of all expansion joints every 40 years. All movement joints should be readily accessible for inspection with space and facility for replacement. Joint details should be designed with the minimum of exposed, level ledges where salt water and debris might accumulate. Run-off from carriageways should not be allowed to penetrate bridge joints. Access requirements should include access ladders, catwalks and landings with sufficient area and lighting for carrying out maintenance and repair work.

**Hangers**

These tension elements are prone to fatigue and corrosion induced wire breaks. Typically these items would require complete replacement every 40 years. The cable protection system and anchorages would need to be readily accessible. Access requirements include access cradles or by abseiling; adequate access for the inspection of deck anchorages from the maintenance access way.

**Deck waterproofing**

This is usually replaced as part of the surfacing replacement maintenance schedule probably every 12-15 years. If a spray epoxy system is used it may be possible to repair the waterproofing one time in lieu of full replacement.

Surfacing

Due to the generally thin layer of mastic asphalt it is usual to replace the entire surfacing system on a suspension bridge. Typically this would require replacement every 12-15 years depending upon traffic loading. This operation requires careful control due to the thin aerofoil deck plate which is very susceptible to damage from heavy planing equipment. Alternatively it may be possible to increase the thickness of the mastic asphalt such that when the worn surfacing is removed, a thin layer is left adhered to the steel plate. The replacement asphalt can then be keyed into the remaining layer. In this way, the risk of damage to the steel plate is reduced and the complexity and programme for the resurfacing is reduced.

Tower saddle / Splay Saddle and Anchorage.

These items usually do not require significant maintenance other than painting but see following comment on main cable dehumidification. Access ladders, walkways and lighting will be provided to assist with inspection and maintenance of these items.

Main Cable dehumidification.

Based on existing maintenance experience from UK suspension bridges and taking account of international trends in new suspension bridge specification it is advisable to anticipate the requirement for a full main cable dehumidification system to be installed at the time of construction. This type of mechanical and electrical installation would have capital costs and ongoing operation and maintenance costs.

Road furniture

Damage and subsequent maintenance frequencies are likely to be similar to all other structures.

Towers

These would have similar maintenance requirements to other marine concrete structures. Minor shipping impact damage repairs are to be expected for light craft and water borne storm debris impact damage. All such maintenance work is likely to be with difficult access either at high level or over water.

Reinforced concrete towers would need to be provided with a suitable treatment to prevent the ingress of chlorides which can cause corrosion of reinforcement. The effectiveness of this treatment should be tested at intervals to monitor chloride levels; replacement or re-application may be required during the bridge lifespan. Towers, if hollow, would have access for inspection inside and all accesses should be weatherproof. Lifts and ladders would be provided within the towers.

Caissons and other Foundations

Access is required for inspection of the caissons (including checks for signs of scour). From time to time the caissons may serve as a mooring point for a floating vessel during maintenance operations. Access should also be provided for this purpose.

Bridge Services, Signage, Warning Instrumentation

It is important that the working of navigation lights, foghorns, aircraft warning lights, road signage can be monitored continuously so that any malfunctions can be rectified immediately. Appropriate access to these services must be provided and any maintenance work must not interfere with bridge traffic.

Maintenance budgets

With the increase in knowledge and specification requirements to control durability it would be reasonable to assume that in the first 20-30 years, the maintenance costs would be generally less than the suspension bridges at Forth, Severn and Humber. This cost will be off-set slightly by the runnings costs required for the dehumidification of the main cable and the main deck if this is also dehumidified.

Within the first 20-30 years apart from regular maintenance, work would be most likely restricted to repainting say every 10 years, resurfacing and deck waterproofing every 12-15 years.

After approximately 30 years bearings, movement joints and hangers will start needing attention and replacement as necessary.

## A3.15 Light Rapid Transit

One of the objectives of a future Forth Crossing is to make provision for a future multimodal crossing solution. This may incorporate light rail or other modes such as guided busways.

The proposed light rail could be accommodated on a new bridge structure in several ways. Each option would need to be explored in detail in terms of how the structure of the bridge would be affected. In the section below several options are briefly described along with the associated effects on the bridge. It is assumed that the light rail would be in combination with two highway lanes. These comments apply to both suspension and cable stayed bridges.

### Single Deck

In this option the tram could be accommodated on the same deck as the road traffic at the centre of the bridge. In order to tie in to the approach tram route both rail lines would need to pass under the main carriageway. With the increased loading and width of deck, it may be necessary to deepen the deck section which in turn affects the vertical alignment.

The weight and size of the deck will increase which will in turn affect the design of the towers, cables, hangers and foundations.

Emergency access will also need to be considered in detail.

**Double Deck**

The introduction of light rail may lead to concerns regarding the visual interference of mixing road and rail traffic on the same bridge deck. A possible solution is to provide a double deck design. It is possible to run the tram along the interior centre portion of the deck in order to keep the vertical alignment as flat as possible, The design of the deck would probably change from a closed torsion box to a trussed deck. The sides of the deck could be enclosed by a structural cladding system. Ventilation would need to be introduced possibly along the centre-line of the bridge deck. Within the box, emergency access routes would be run either side of the trams.

The width of the new bridge would be similar to that proposed in the Setting Forth option. In order to accommodate the train loading and provide sufficient headroom, the depth of the deck section would need to be increased. As an example, the Tsing Ma Bridge with a similar main span of 1377m and deck width of 41m has a deck depth of 7.6m . This increase in depth will affect the vertical alignment of the approach roads and lead to an increase in cost of the approach embankments.

The increase in depth of the deck will lead to an increase in weight which will in turn affect the design of the towers, cables, hangers and foundations.

There are only a few cable supported bridges in the world that carry rail loading. Table A.2 lists all known such bridges with a span exceeding about 500 metres

**Table A.2 Cable Supported Bridges with Rail Loading**

| Bridge | Type | Span | Rail loading |
|---|---|---|---|
| Tsing Ma, Hong Kong | Suspension | 1377m | 2 tracks, (airport shuttle trains) |
| Tagus, Lisbon, Portugal | Suspension | 1013m | 2 tracks, (passenger & goods) |
| Minami Bisan-Seto, Japan | Suspension | 1100m | 2 tracks, provision for 2 tracks for bullet train |
| Kita Bisan-Seto, Japan | Suspension | 990m | 2 tracks, provision for 2 tracks for bullet train |
| Shimotsui-Seto, Japan | Suspension | 940m | 2 tracks, provision for 2 tracks for bullet train |
| Ohnaruto, Japan | Suspension | 864m | Provision for 2 tracks for bullet train |
| Rainbow, Japan | Suspension | 570m | 2 tracks, medium (passenger) |
| Øresund, Denmark/Sweden | Cable stayed | 490m | 2 tracks, heavy |

## A4 CABLE STAYED BRIDGES

Cable stayed bridges are also technically feasible across the Forth. However, due to the width of the Firth, and span limitations, it would inevitably require a tower foundation located in the deeper water close to the centre of the Firth unless use can be made of an island such as Beamer Rock. With current technology spans of approximately 1000m can be achieved. The maximum existing cable stayed bridge span is 890m on the Tatara Bridge in Japan. The towers are 224m high making them 66m higher than the Forth Road Bridge. Construction is currently underway on the Sutong cable stayed bridge in China with a maximum span of 1088m. Several cable stayed bridge options were developed in the Setting Forth project with maximum spans of 650m. As noted above, with improvements in technology, increased spans can now be achieved. Rion-AntiRion Bridge, Greece, pictured below was opened in 2004. It has maximum spans of 560m and its foundations are founded in water up to 65m deep. (See Figure A.7 below)

**Figure: A.7 Rion-AntiRion Bridge, Greece**

The approach viaducts associated with cable stayed bridges would tend to be longer than those associated with suspension bridges as the main span of a cable stayed bridge is more limited in length than that of a suspension bridge. The Oresund Bridge between Sweden and Denmark has a maximum span of 490m and carries combined rail and road.

The advantages of cable stayed bridges compared to suspension bridges are:

- slightly shorter construction programme; and
- construction of the foundations at the landfalls are less complex than those for a suspension bridge as they do not need to provide tension anchorage. The foundations and substructure are relatively simple abutments. As a result of reduced excavation the potential problems associated with the presence of methane on the south landfall could be reduced.

The disadvantages of cable stayed bridges are:

- they have shorter spans than suspension bridges, leading to an increased number of piers and foundations in the Firth. It is likely that the foundations would be sited in deeper water than those of a suspension bridge, with a commensurate increase in construction risk affecting costs and contract duration;

- the increased number of piers in the Firth would have a greater environmental impact and would increase the blockage of the Firth; and

- although there are significant construction risks associated with the erection of suspension bridge main cables, the risks associated with the deck erection of a cable stayed bridge also need to be carefully managed (see section A.4.4. below).

In the following sections the design considerations affecting a cable stayed bridge are presented.

## A4.1 Typical Construction Sequence

The construction of a cable stayed bridge deck typically uses a cantilever approach. The broad sequence of activities is as follows:

- construct foundations;

- construct towers and abutments;

- erect cantilever deck sections progressively with cable stays; and

- install finishes (road surfacing, bridge deck furniture, communications etc).

## A4.2 Foundations

A cable stayed bridge requires competent rock in order to provide a sound foundation for the main towers and abutments. The foundations at the abutments are less complex than those of a suspension bridge as there is no requirement for tension anchorages. It is not necessary therefore to tunnel into the ground at the landfalls. This is of particular importance on the south landfall at Queensferry where methane was discovered during the construction of the Forth Road Bridge, should this location be selected for any future crossing.

The foundation construction methodology for the main towers would be similar to those of a suspension bridge. Typically this would involve the construction of a sheet pile cofferdam within which the reinforced concrete caisson would be constructed.

The main risks associated with foundation construction are linked with working in deep water. One of the disadvantages of a cable stayed bridge compared to a suspension bridge is that the latter can be designed such that its main towers are located in shallow water or dry land. With the shorter spans achievable with cable stayed bridges the foundations are more likely to be located in the deeper parts of the Firth.

## A4.3 Towers

The tower construction method would be similar to the suspension bridge and could be constructed using reinforced concrete or steel.

### A4.4 Deck and Cables

The individual panels for the deck units would probably be manufactured in a steel fabricator's works and transported to a local construction site for assembly into units.

The completed deck units would be transferred to a barge and taken out to the deck erection front. The deck would then be lifted into place supported by the inclined cable stays. The deck would be cantilevered out from both sides of each tower in order to minimise out of balance loads on the towers and their foundations.

The main risks associated with deck erection relate to the weather and the slenderness of the cantilever decks. As the cantilevers reach their maximum length just before the sections meet, the deck is at its most vulnerable condition for resistance to wind loads.

### A4.5 Construction Programme

A review of the construction duration for the world's longest main span cable stayed bridges has been made in order to assist in estimating the construction programme for cable stayed options across the Forth.

The maximum spans of the bridge options outlined for the corridors would be approximately 650m. The construction sequence is complicated by the fact that the crossing requires two main spans with a common central tower. Rion-Antirion bridge in Greece consists of several multiple spans and is a reasonable indicator of the construction period. It can therefore be expected that the construction period would be in the region of five to six years.

**Table A.3 – World's Longest Cable Stayed Bridges**

| Ranking | Name | Span (m) | Completion Date | Construction Duration (Years) |
|---|---|---|---|---|
| 1 | Sutong, China | 1088 | Expected 2009 | |
| 2 | Stonecutters, HK | 1018 | Expected 2008 | |
| 3 | Tatara, Japan | 890 | 1999 | 6 |
| 4 | Pont de Normandie, France | 856 | 1995 | 7 |
| 5 | Second Yangtze | 628 | 2001 | 4 |
| 6 | SkyBridge, Canada | 616 | 1990 | ? |
| 7 | Rion-Antirion, Greece | 560 | 2004 | 6 (including dredging ) |
| 8 | Skarnsund, Norway | 530 | 1991 | ? |
| 9 | Kohlbrandbrucke, Germany | 520 | 1974 | 4 |
| 10 | Mumbai, India | 500 | | |

## A4.6 Future Maintenance

Cable stayed bridges would have similar maintenance considerations to those outlined in 5.3.14 for suspension bridges.

## A4.7 Risks associated with Suspension Bridges and Cable Stayed Bridges

The construction risks associated with suspension and cable stayed bridges are highlighted in the relevant sections relating to the various stages within the construction sequence. These risks are generic regardless of the final alignment.

The design and construction risks are summarised below in Table A.4:

**Table A.4 – Summary of Design and Construction Risks**

| | Suspension Bridge | Cable stayed Bridge |
|---|---|---|
| **Design process-Permanent works** | The design process for a suspension bridge is the most complex of the large span bridge forms. The programme risk of delays in design is high with more complicated and longer duration design processes. | The design process complexity for a cable stayed bridge is generally recognised as lesser than that for a suspension bridge. This results in a degree of reduction in the construction programme risk |
| **Design process-Temporary works.** | The temporary works requirements for suspension bridges are the most onerous. Temporary works include the temporary footways for cable spinning, cable spinning equipment, deck erection lifting equipment. | Temporary works are complex. But temporary works for stay erection are slightly simpler than suspension cable installation. Also deck mounted lifting gantries are slightly less complex than suspension bridge deck erection equipment. |
| **Anchorage construction – Ground conditions risks.** | Some projects have experienced delays as a result of unforeseen ground conditions at anchorages and unpredictable subsequent ground movements | Cable stayed bridges only require nominal abutment structures and are not nearly as susceptible to the risk of ground conditions |
| **Foundation construction** | Construction of foundations in deep water carries high risk | Construction of foundations is likely to be more risky than for a Suspension bridge as there will be more foundations. Also for corridors other than D where Beamer Rock can be |

| | | |
|---|---|---|
| | | used the central pier will be in significantly deeper water. |
| **Tower construction** | The process and associated programme risks are similar for both suspension and cable stayed bridges. Main risk is associated with the weather | The process and associated programme risks are similar for both suspension and cable stayed bridges. Main risk is associated with the weather |
| **Approach viaducts** | The process and associated programme risks of working in tidal water are similar for both suspension and cable stayed. However the amount of approach viaduct will probably be less for a suspension bridge | Similar to suspension bridge risks but slight elevation of risk due to the generally longer length of approach viaduct |
| **Main cable–Temporary footbridge erection** | This is a relatively high risk activity and can typically take 3- 4months to complete. It is on the critical path therefore delay will directly result in project delay. Main risk is associated with the weather. | There is no requirement for a temporary footbridge on a cable stayed structure. |
| **Main cable–Aerial spinning** | This process is a complex and specialist activity. It is on the critical path. It is probably slightly more prone to weather restrictions (wind speed and visibility than the alternative preformed parallel wire strand construction. | There is no equivalent activity on a cable stayed bridge |
| **Main cable–Preformed Parallel Wire Strand (PPWS).** | This process is also fairly complex but slightly less so than cable spinning. The primary disadvantage relative to spinning is the increased cost of the larger anchorage. It is probably slightly less prone to weather and poor visibility risks than spinning. In general it is a less specialist activity. Total duration is usually similar to spinning. The expected quality of a | There is no equivalent activity on a cable stayed bridge |

| | | |
|---|---|---|
| | PPWS cable is generally higher and is therefore preferable to an aerial spun cable | |
| **Deck erection gantries** | Design commissioning and erection onto cables. This is a fairly specialist activity . There have been delays to the erection of cable mounted gantries on a number of major projects for a variety of reasons. | Design commissioning and erection onto the first deck This will generally be a slightly simpler and lower risk activity than erection onto cables. |
| **Deck unit connection and Erection** | The processes and durations are reasonably similar between a suspension bridge and a cable stayed bridge. | The processes and durations are reasonably similar between a suspension bridge and a cable stayed bridge. The erection of the deck as it cantilevers from each tower has a risk in high wind particularly as it nears completion. |

## A4.8 Construction Impacts

The construction of long span bridges across the Firth of Forth will inevitably have an impact on the local area and its environment. Measures will be required to mitigate these impacts during the design and construction phases of the Project in accordance with current best practice. A summary of the likely major impacts is given as follows:

Noise, Dust and Dirt

Construction processes are generally noisy, dusty and dirty. The impact of these can be mitigated by the specification of good working practices and inclusion of specific requirements to avoid the nuisance caused to the general public and bridge users. Where possible this work will be carried out during normal daytime working hours and these hours would be controlled within the construction contract. At times it may be necessary to carry out work at night to minimise disruption to the public. This will need to be carefully stated and publicised to minimise disruption.

Work Compounds

It is likely that work compounds would be set up on both North and South shores. These compounds would be used for the storage of plant equipment and materials, workers welfare facilities and for fabrication and component assembly. The compound must be easily accessible by road. In addition the likely construction method would involve the delivery of prefabricated sections to the work front by boat. The compound would need to be located at the shore or temporary tracks would be required to facilitate delivery of materials to the navigable water.

Construction Traffic

The most likely construction method would involve the delivery of large quantities of prefabricated materials to the works compounds. This would increase the volume of traffic locally. Possible methods of mitigation would include the delivery of materials at night.

Disruption to Road Traffic

Some traffic delays would be experienced during the work to tie in the approach roads to the existing network.

Disruption to Water Traffic

As discussed above, the likely form of construction would involve the delivery of large prefabricated deck sections to the work front by water. This work would need to be carefully co-ordinated with the relevant parties including Forth Ports and Rosyth Docks. Depending on the corridor chosen, the work may lead to a change in the berthing positions for ships in the middle of the Firth. The zones around any new bridge piers would need to be protected during construction and the will also be provided with protection against ship impact in its completed condition.

Control of Pollution

The Firth of Forth would be controlled from pollution in accordance with good working practice. This would include containment wherever possible to prevent materials and tools from falling into the water.

Environmental Impacts

The generic environmental constraints are listed in Chapter two and the impacts relating to ecology, landscape, archaeology and cultural heritage and planning designations for the specific corridors are listed in Appendices B to F.

## A5 DISCUSSION OF TUNNELLING METHODS

### A5.1 Introduction

Tunnelling methods may be categorised into the following four types according to the method of construction:

- Bored, utilising a Tunnel Boring Machine (TBM);
- immersed tube;
- cut and cover; and
- mined tunnel.

Construction of a Forth Tunnel is likely to require a combination of methods. These are likely to involve a method for the main crossing, supplemented by methods to create sections of the tunnel approaches under the adjacent banks of the Forth.

## A5.2 Bored Tunnel

A Bored tunnel which utilises 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 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. For this type of project a TBM would more likely be launched from a cutting that would later form the approach ramp for the tunnel. 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.

### Bored Tunnel Lining

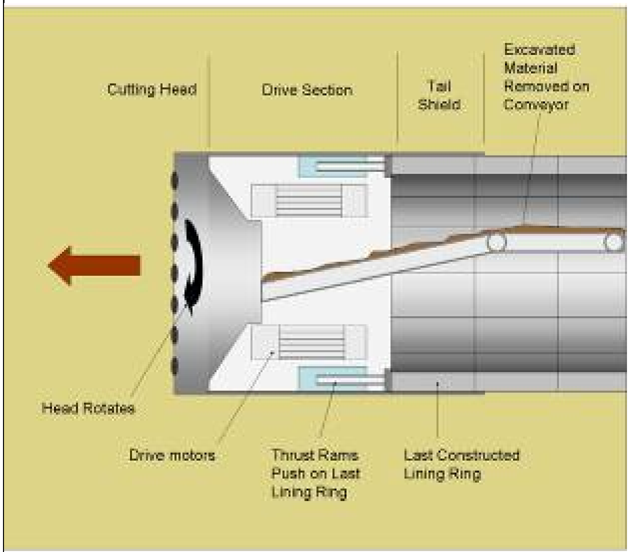
Tunnels excavated entirely in competent and dry rock may require no structural lining behind the boring machine and therefore no tail shield is required. While there may be areas of high strength Dolerite rock along TBM alignments, it is anticipated that significant areas of loose materials and high groundwater pressures would be encountered, therefore a lining would be assumed throughout any proposed tunnel.

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. A segmental lining is grouted in place to maintain its shape and to provide additional waterproofing. The available information suggests that there will be high groundwater pressures and areas of soils and rock that will not be self-supporting. A watertight segmental lining would be anticipated.

## Excavation Sequence

Bored tunnelling involves a two stage cycle to create the tunnel bore.

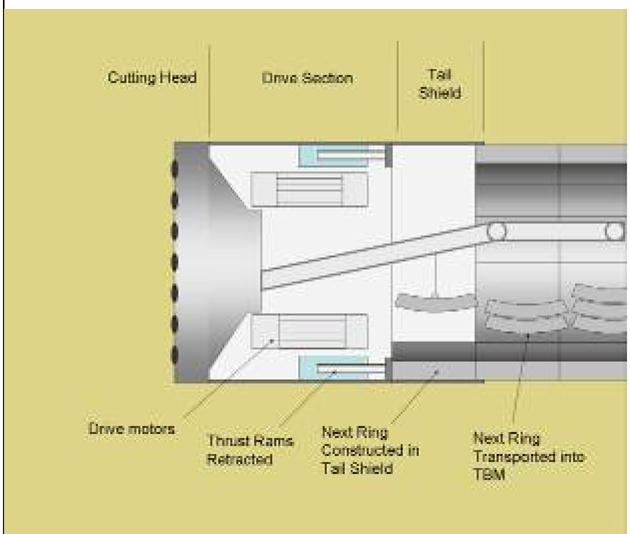
**Stage 1 - Excavation Advance**




- 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.

**Stage 2 – Lining Erection**



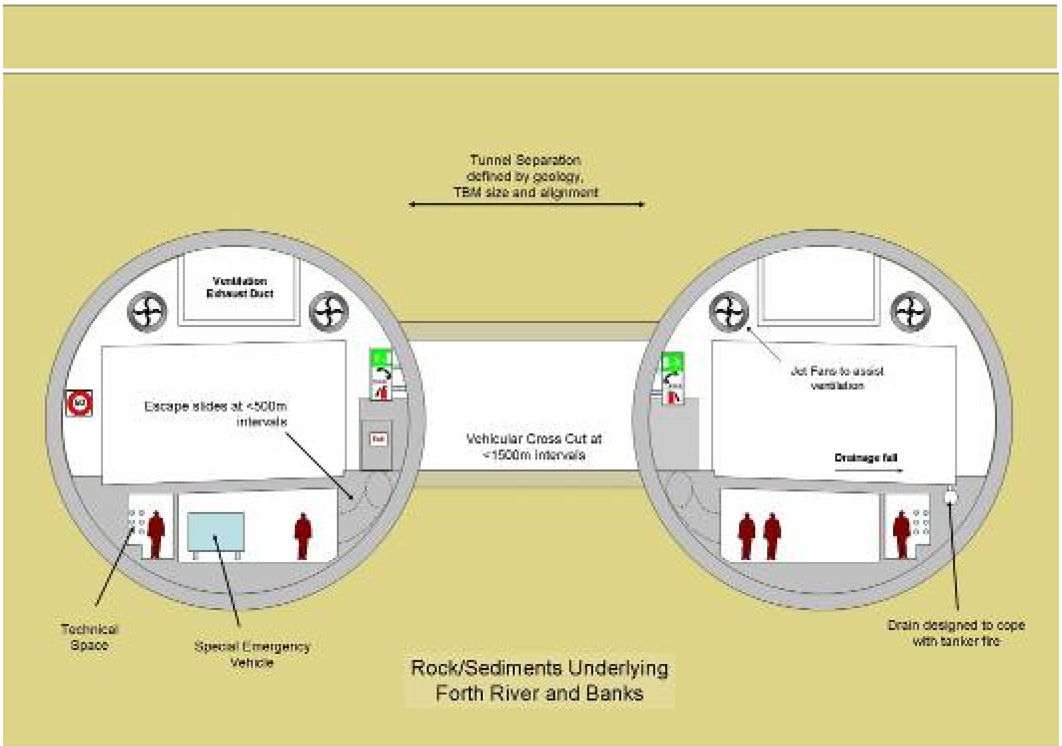

- The thrust rams are withdrawn into the Drive Section leaving clear space for the erection of the lining
- Each segment forming the lining is manoeuvred into position and bolted together to form a completed lining ring

The thrust rams are then re-engaged to commence the next excavation cycle

## A5.3 Forth Crossing Bored Tunnel

Tunnel Size. This is dictated by a number of factors that include carriageway width and height, ventilation requirements and safety provisions. There are two main methods of satisfying the safety requirements for a Forth tunnel constructed by TBM, each has an effect on the tunnel diameter. These approaches are differentiated by the means of emergency escape. The most common method of escape used in similar road tunnels has typically involved escape to the adjacent tunnel by means of a cross-connecting tunnel. A schematic layout of this configuration is shown in Figure A.10.

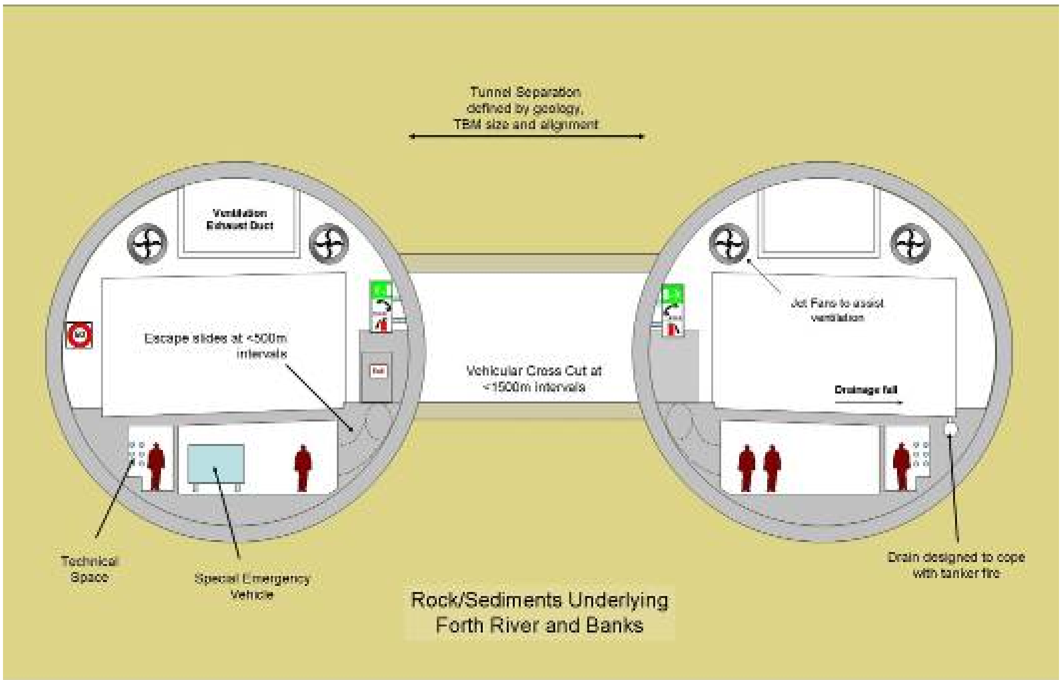
**Figure A.10 – Schematic of bored tunnel using cross-passage escape**




During an emergency the cross passage is pressurised to prevent inflow of smoke or fumes and, typically, traffic is prevented from entering both tunnels. The non-incident tunnel is then cleared of traffic already present to allow access by emergency services. Emergency vehicles may also enter the incident tunnel. At this stage the ventilation system would manage smoke to assist evacuation. Drivers would escape via the cross passages into the adjacent tunnel. This configuration generally requires a TBM of approximately 12m diameter. Construction of the cross passages can be costly and may require specialist ground treatment, dependent on ground conditions.

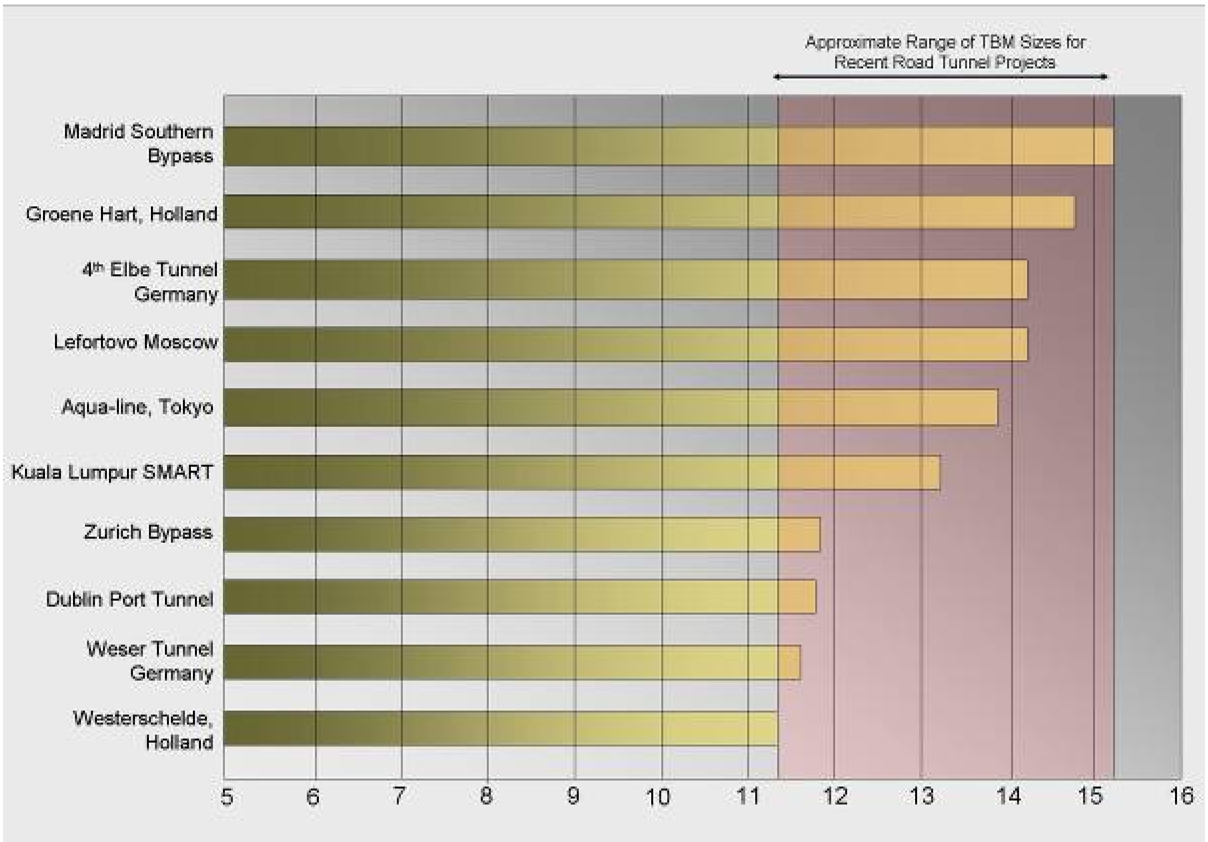
For the Forth, the available ground condition information suggests that a deep glacial channel exists below the Forth. This would have to be confirmed by ground investigations. If the construction of the cross passages took place in this buried channel significant ground treatment may be required. In such cases construction costs could be enough to reduce the financial viability of the project. If this was the case, the escape routes could be altered to incorporate them into a larger bored tunnel. A schematic layout of this configuration is shown in Figure A.11. The selection of the bored tunnel diameter would be carried out during the design process, after site investigation had taken place.

**Figure A.11 - Schematic of bored tunnel Using Escape Chutes**




In this case drivers would escape via means of a slide to a pressurised area below the road deck. This would also act as a route for emergency services using specially designed vehicles stored in the tunnel. Cross-connections would be required every 1500m to allow emergency vehicles to cross between tunnel bores. This configuration generally requires a TBM in excess of 13m and places the machine required towards the upper end of the range of boring machine sizes currently available. Figure A.12 summarises the size range of recent major road projects that used bored tunnel methods.

## Figure A.12 - Range of TBM Sizes for Recent Major Road Schemes




Ground conditions. These 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 the increased power requirements to provide sufficient thrust and to turn the cutting head in harder ground conditions.

A bored tunnel alignment beneath the Forth 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 river; and
- Dolerite dykes closer to Beamer Rock and the existing bridges.

Current TBMs of the size range required have been configured for projects that include rock similar to the coal measures and alluvial deposits anticipated. However, if large sections of dolerite were present on the alignment it may not be possible to construct the tunnel with the larger of the two bored tunnel configurations identified. Therefore, alignment selection would seek to avoid areas of dolerite where possible so that selection of a larger TBM is not necessarily precluded.

The alignment selection would also seek to minimise the risk of encountering old mine workings where identified. Site investigation would be required to verify ground conditions ahead of design and construction.

Bored tunnelling has a considerable and recent track record, delivering projects similar to the tunnel that would be required beneath the Forth. Figures A.12 to A.14 illustrate key statistics from a number of recent bored tunnel projects of similar scope and size.

**Figure A.13 - Approximate Length of bored tunnel Alignments for Comparable Projects**

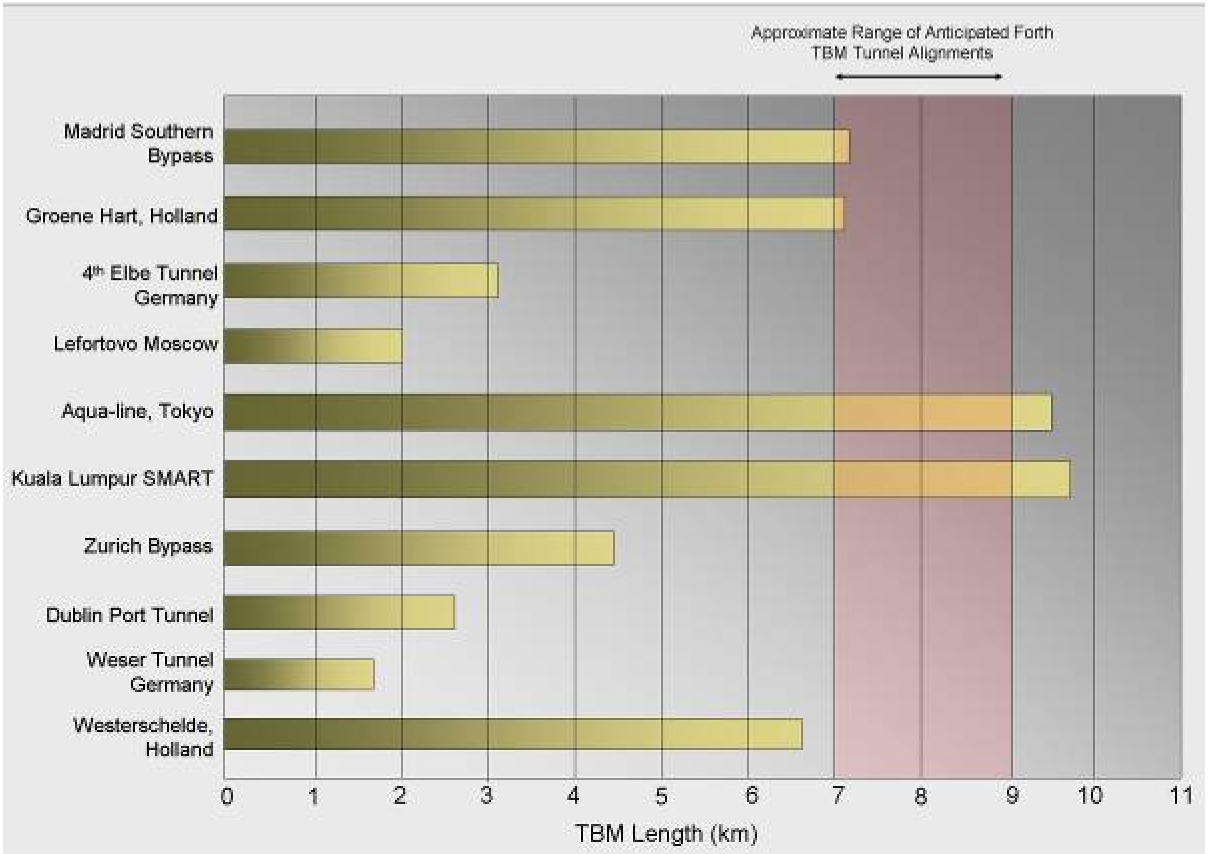
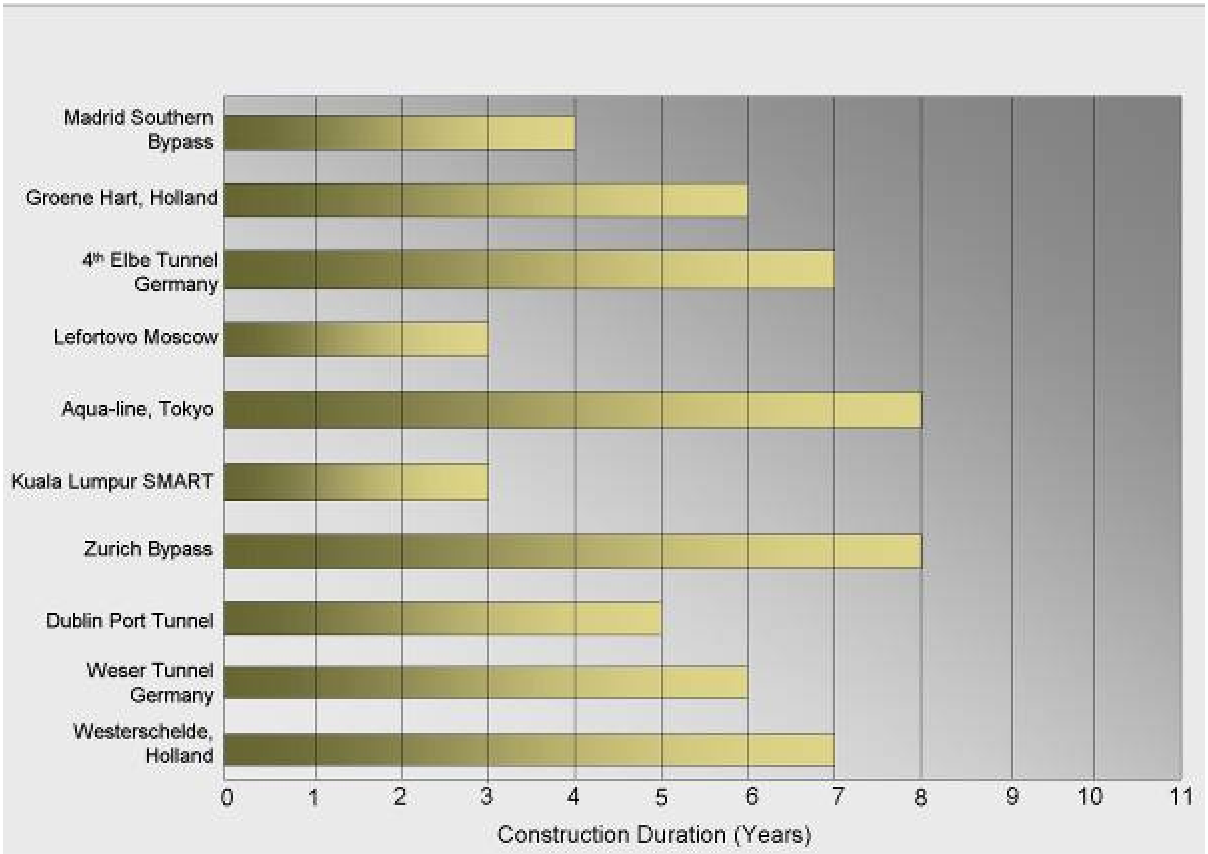


**Figure A.14 –TBM  Construction Durations for Comparable Projects**




Although the length of overall tunnelling required would put the scheme amongst the longest river crossing tunnels constructed to date, tunnelling may be broken into discrete construction packages to accelerate progress and to allow equipment to be optimised for the likely tunnelling conditions.  This also facilitates an accelerated construction programme.  This is different from the bridge options where there is less opportunity to have concurrent construction stages.  The overall construction duration is dependent on the number of tunnelling packages and is therefore related to the method of procurement.

When under the Forth a bored tunnel must be in the stable deposits and clear of any effects of short term riverbed changes, dredging and possible influences of ship impact.  The vertical alignment is influenced by the depth of the channel and would be optimised during design.  Site investigation will be required to define the minimum depth of tunnelling below ground surface and riverbed levels.  For planning purposes the minimum depth of the tunnel crown below riverbed is 1.5 times the anticipated tunnel diameter.  Water depths are based on those indicated by the current admiralty charts.

A TBM will be capable of tunnelling through most of the likely ground conditions without affecting SPA, SSSI, Ramsar and other designated sites along the banks of the Forth.  However, environmental effects would have to be managed at each portal and for disposal of excavated material. The TBM can start and finish tunnelling with approximately one diameter of cover, although this can be reduced under certain circumstances. Therefore, an approach ramp or large shaft is generally required at either end of the bored tunnel.

Significant site investigation would be required to define areas of hard dolerite rock and the risk of encountering mine workings. This may require drilling and sampling in the Forth and may include work within environmentally designated sites.

### A5.4 Immersed Tube Tunnels

Many marine tunnel crossings have been constructed using the immersed tube method. This is particularly suited to road tunnel construction as roadways may be compartmentalised within the same structure, assisting floatation and positioning. This method is generally only suited to construction in deeper water although it may be extended to areas in and above the littoral zone by creating temporary canal structures. It is often used in areas where the alignment, geology or other physical constraints make the use of a bored or mined tunnel difficult. Generally the approaches to the immersed tube river crossing section are cut and cover tunnels through the river banks, although bored approach tunnels have been used where topography requires.

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 construction materials is likely to be dependant on the availability of local skills, materials and facilities.

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

- Unit Size
- Unit Fabrication;
- Bed Preparation;
- Unit Positioning and Fixing; and
- Fill/Armouring.

#### 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 if divided up, particularly if the foundation sediment causes 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, changes in gradients, vertical alignment or horizontal curvature and differential settlement of the tunnel foundation layers. For a Forth crossing, single units of approximately 30m wide by up to 100m long would be anticipated.

## 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. There are many commercial and naval docking facilities in the area; their suitability for use as immersed tube casting docks would need to be evaluated. However, in this case the size of dock required, the considerable adjacent work areas required and the availability of these facilities means that for planning purposes it would be assumed that a new temporary casting facility would be required. Generally this facility would be located within the Firth of Forth close to the tunnel alignment. Where possible it would be located close to an existing river channel, deep enough to float the immersed tube units. It must be assumed that dredging would be required to allow the units to be transported from the dry-dock.

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 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 are present, mechanical cutting or blasting may be required. Blasting is considered undesirable and the alignments would be altered to reduce or eliminate its use. 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.

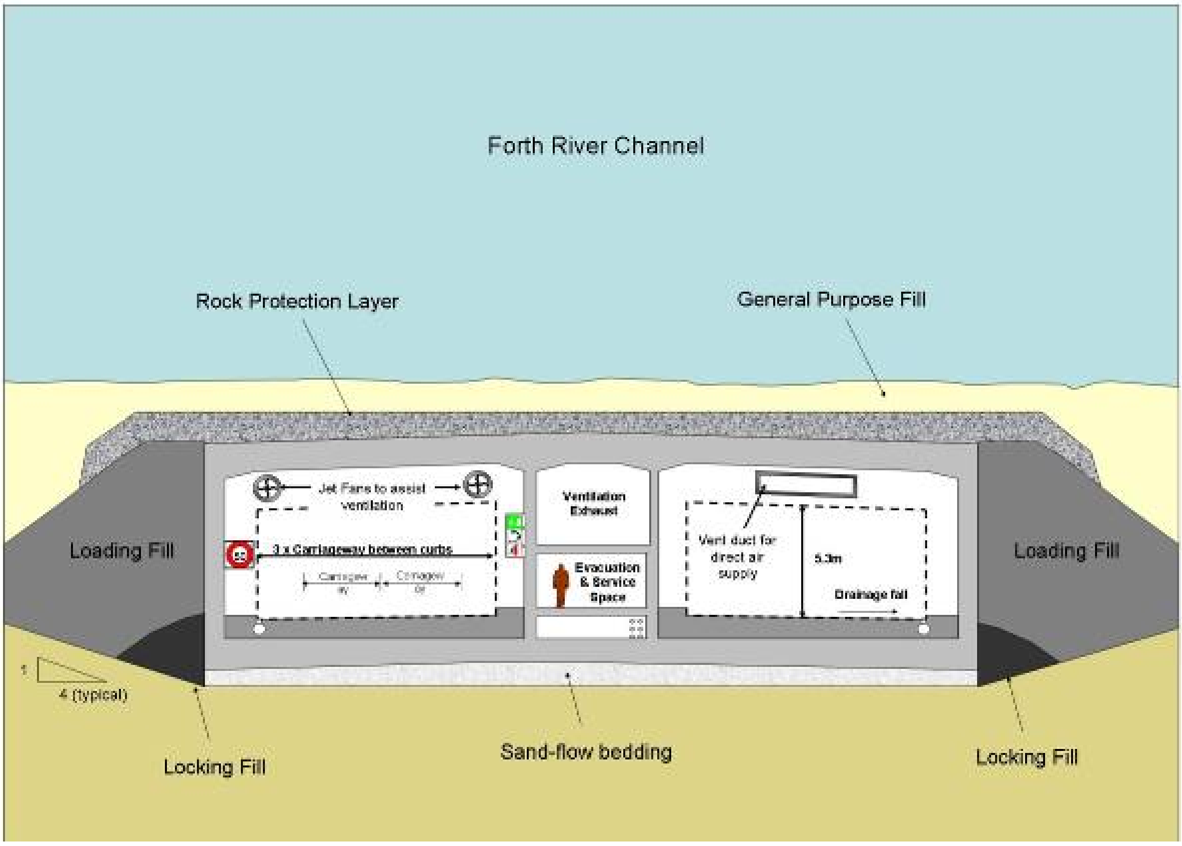
It is common that immersed tubes are constructed in river estuaries that are in urban environments where historic industrialisation has polluted the sea or freshwater. Often contaminants remain in the deposited estuary sediments. As with all underwater excavation these sediments would be released and the Forth would not be any different. If pollution was present then this would likely be released over a relatively short period. Careful site investigation and testing of sediments is needed to identify any potential environmental risks and allow these 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 units, water will 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 place before the fit out of the structure. When designed as negatively buoyant, the structures will only float with the assistance of barges either side of the unit. The barges are used as a platform to lower the units into position. Positive buoyancy is generally preferred as there is inherently less risk in 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 to assist positioning. The sand is passed through pipes cast into the base and side walls of the units. In these conditions the sand is self compacting. The joints between the unit are formed by the use of OMEGA shaped rubber gaskets. The joint is compressed by removing the water outside adjacent bulkheads and water pressure on the exposed end of the placed unit compresses the joint.

**Figure A.15 - Generalised Schematic of Typical Immersed Tube Tunnel**




## Fill/Armouring

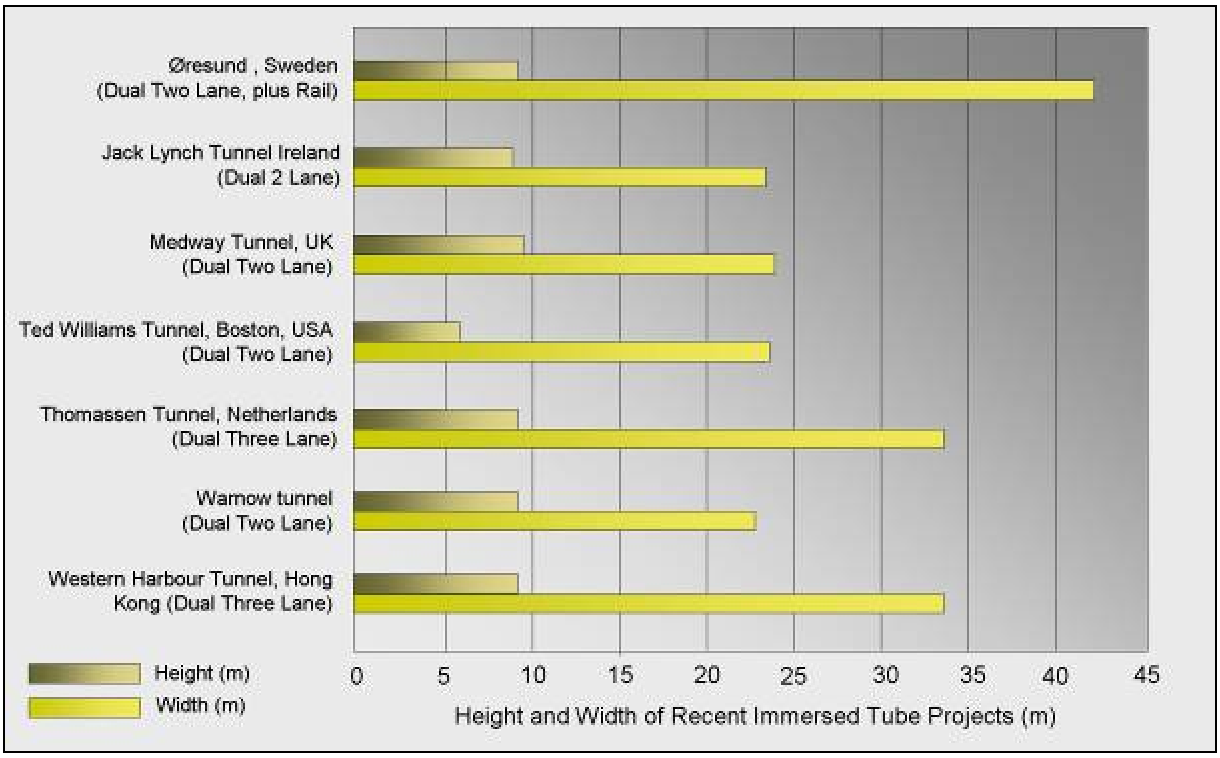
When all units are secured and the ends of the tunnel are constructed to a point above flood level the fill and armouring is constructed to protect the tunnel from ship and dredging impact. It also assists in holding the tunnel in position once the tunnel water ballast tanks within the unit are drained. Internal fit-out of the tunnel roadway and internal systems may then commence.

## A5.5 Forth Crossing Immersed Tube Tunnel

The immersed tube method is flexible in terms of unit width, height and length. Therefore, a number of different escape and ventilation configurations can be incorporated. Figure 5.16 illustrates the range of immersed tube tunnel sizes for recent immersed tube projects. As the figure demonstrates dual three lane road widths are possible using this method. The older projects noted may not be in compliance with the 2007 regulations.

An immersed tube may also incorporate a permanent light rail or guided busway in addition to the dual two-lane roadways by widening the tunnel. This approach was used to incorporate a dual rail and road tunnel for the immersed tube sections of the Oresund Link between Denmark and Sweden.

### Figure A.16 - Size of Various Recent Immersed Tube Projects




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 Forth sediments do not appear to present a problem for an immersed tube tunnel.

Although an immersed tube is essentially a shallow marine tunnel, it can still be affected by mine workings, even if significantly below the riverbed. The British Geological Survey Drift Edition mapping of Edinburgh (Sheet 32) indicates that “sand, gravel and boulders entered mine at -680ft OD” mid-river at Bo’ness. Therefore investigation must be carried out and, if possible, realignment to avoid such mine workings.

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

Alignments in corridors A to C to the west of Rosyth would generally have a reduced chance of encountering dolerite.  However, the incidence of old mine workings under the Forth is thought to increase westwards.

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 pollution 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 Firth are almost exclusively designated as SPA or SSSI.  Although the construction of an immersed tube would not necessarily directly affect these areas sediment release from construction is likely to affect them.  The approach structures for the immersed tube tunnel may be bored or cut and cover tunnels.  If cut and cover is used this would have a direct impact on the banks, shoreline and littoral zone.

As the immersed tube method is a marine-only method its length is dependent on the width of the river/estuary.  An immersed tunnel would therefore be shorter for corridors C and D.  Alignments in corridors D and E would cross deep channels, although this does not preclude the use of immersed tube tunnels, it is likely to increase the cost for the tunnel and difficulty in maintaining the three per cent target maximum gradient.  It would also be difficult to minimise the gradients of the approach tunnels in this area.

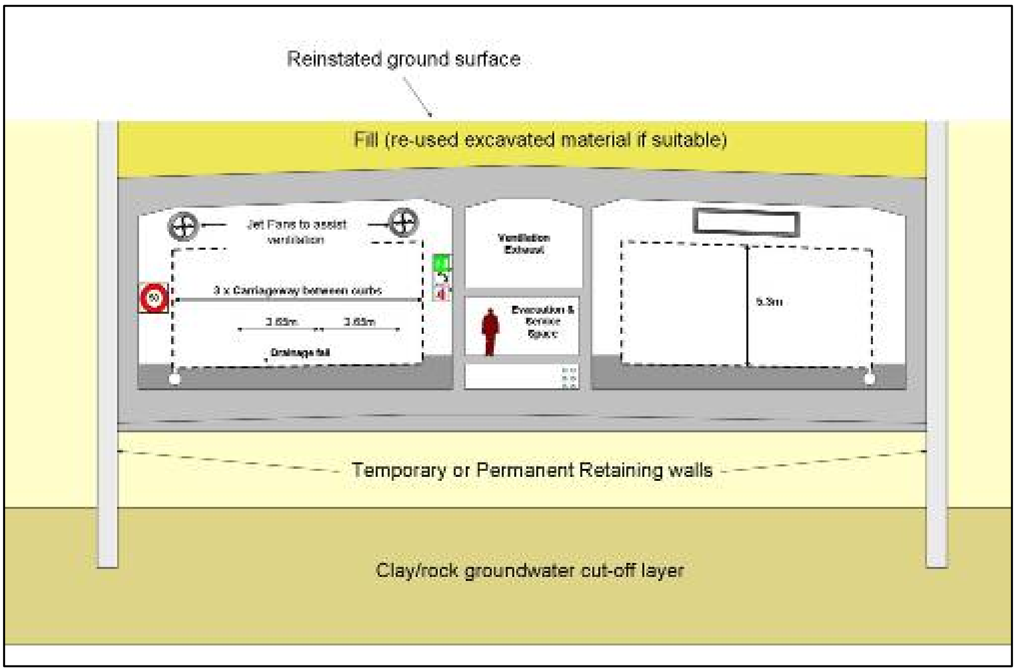
As the Firth of Forth is in a valley sloping up steeply from the shoreline to higher ground on each bank, any shallow marine immersed tube would have to either rise steeply in cut and cover or large open cut to reach the M9 or M90 or do so by going into a bored tunnel.  This may have benefits in allowing a reduction in tunnel depth under the Forth, thus shortening the overall alignment.  It may also reduce the geological risks associated with TBM excavation through mixed soft sediment and dolerite.  The steepness of the river valley generally diminishes to the west of the study area and therefore the use of the immersed tube method becomes more compatible with alignment corridors A and B.

Construction that would have significant direct or indirect impact on an SPA must be carefully evaluated.  Generally, methods impacting SPAs would only be selected if there were no other reasonable alternative method available.  In this case it has been assumed that a bored tunnel crossing is a valid and reasonable alternative for the main water crossing.  Therefore, immersed tube tunnels are not considered as the principal method of construction for the majority of Forth Crossing tunnel alignments.

### A5.6 Cut and Cover Tunnel

Cut and cover tunnels are similar to immersed tube tunnels in that they are shallow tunnels constructed in a trench. They are primarily land-based methods and are not suited for deep river/estuarial crossings. They have been used in shallow marine environments and could therefore be considered for littoral and shallow sub-littoral zones.

**Figure A.17 - Schematic Through a Typical Cut and Cover Tunnel**




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

- Excavation and Support;
- Tunnel Fabrication; and
- Reinstatement.

Excavation and Support.

The initial "cut" is undertaken to facilitate the tunnel construction. This uses similar technology to road cuttings. Prior to excavation, buried utilities and services crossing the route have to be protected, temporarily raised or permanently diverted to avoid the tunnel alignment where possible. 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, in soft rocks and soils stable slopes may be created by constructing benches. 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, incorporated into the final structure or temporary and removed or abandoned after the tunnel structure has been completed.

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 tunnel forms. As considerable materials and excavated fill storage is required this operation requires a significant work site.

Reinstatement.

After construction, fill is used to reinstate the ground surface. Where possible this fill may be reserved material from the trench excavation. Additional fill 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. In some cases this offers the opportunity to improve surface conditions, such as utility and drainage improvements or local road upgrades.

Cut and cover tunnelling has been used to construct similar projects and is likely to be considered for use for a Forth tunnel. It is not suitable for marine crossings but could be used to reduce the impact of a deep immersed tube tunnel. The shallow and inter-tidal sections of an immersed tube crossing could be constructed using cut and cover techniques. This could limit (but not eliminate) the sediment disturbed and released by construction.

As with immersed tube tunnels, the use within the SPA is generally only possible if no other reasonable alternative is available. Again a bored tunnel is considered a reasonable alternative to marine cut and cover at this time. The cut and cover method is only therefore to be considered as a method for constructing limited lengths of tunnel on land and in particular for constructing the approaches to the bored tunnel.

## A5.7 Mined Tunnels

This is a generic term covering mechanically excavated tunnels, or tunnels constructed using drill and blast techniques. Sequenced excavation is used to create non-circular, or variable section tunnels. If ground conditions are favourable, tunnels of the size required for a dual two-lane tunnel can be excavated.

This method relies on the excavation and support of competent ground. Thus significant ground treatment of non-competent ground may be necessary to allow mining to take place. As this method relies on the ability of the ground to temporarily support itself, it can have limited application in the sands and gravels under the Forth, particularly if accompanied by the high water pressures that would be expected. Ground treatment of large sections of a mined alignment is not considered practical or desirable. Therefore, this method is considered to have limited application for a Forth Tunnel. It is most likely to be considered for creating ventilation access points, cross passages and vehicle crossovers required between bored tunnel bores.

## A6 SUMMARY OF BRIDGE AND TUNNEL METHODS

A summary of all the main issues associated with suspension bridges and cable stayed bridges is presented in Table A.5. A bridge crossing is technically feasible. A suspension bridge or cable stayed bridge requires competent ground material for the bridge pier foundations. Multi span approach viaducts are required in combination with the main cable supported bridge spans.

A summary of all the main issues associated with the four different tunnelling methods is presented in Table A.6.

A tunnelled solution for the replacement Forth Crossing is considered feasible and has international precedent. Bored tunnelling utilising a TBM is considered the most desirable of the tunnelling methods as it would avoid the main environmental problems associated with immersed tube tunnelling. It is considered that because bored tunnelling is seen as a reasonable alternative that does not impinge on the various SPAs and SSSIs that delineate the banks of the Forth, immersed tube tunnels should not be considered further in corridors A to D.

To account for the limited geological information available east of the existing Forth (rail) Bridge a combined bored/immersed tube option has been retained in corridor E. This will have to be balanced against the anticipated potential increase in environmental impact.

Mined and cut and cover tunnelling are considered as supplementary methods to the main (bored) crossing under the Forth.

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**Table A.5 – Summary of Bridge Structural Types**

| Issue<br><br>Method | Technically Feasible for Forth Crossing Bridge ? | Geological Constraints | Environmental Issues | Can incorporate multi-modal use in permanent case? | Proposed use for Forth Crossing Bridge |
|---|---|---|---|---|---|
| Suspension Bridges | Yes<br><br>Bridge spans are long but within limits achieved across the world<br><br>Wind-shielding can be provided to significantly reduce restrictions or diversions for wind susceptible vehicles | Requires competent rock at a reasonable depth below the Firth bed level for bridge towers.<br><br>If competent rock is not present at the landfall areas, gravity anchors rather than tunnelled anchorages can be provided | Impact on areas of SSSI, SPAs and landscaped areas likely .<br><br>Impact on archaeology and ancient monuments likely.<br><br>Impact on urban built up areas likely | Yes. A widened bridge deck or double deck can be provided. | Feasible method for Forth Crossing in combination with multi span approach viaducts |
| Cable Stayed Bridges | Yes. Bridge spans are less than suspension bridges but within limits achieved across the world. For feasible, economic foundation for central pier, rock outcrop such as Beamer Rock is required<br><br>Wind-shielding significantly reduce restrictions for wind susceptible vehicles. | Requires competent rock at a reasonable depth below the Firth bed level for bridge towers<br><br>Geology at ends of main bridge not as constrained as suspension bridge as tension anchorages are not required. | Direct and indirect effects on SPA, SSSI and landscaped areas likely<br><br>Impact on archaeology and ancient monuments likely.<br><br>Impact on urban built up areas likely<br><br>Additional impact on middle of Firth eg Beamer Rock | Yes. A widened bridge deck or double deck can be provided. | Feasible method for Forth Crossing in combination with multi span approach viaducts |

**Table A.6 – Summary of Tunnelling Methods**

| Issue / Method | Technically Feasible for Forth Crossing Tunnel? | Geological Constraints | Environmental Issues | Can incorporate multi-modal use in permanent case? | Proposed use for Forth Crossing Tunnel |
|---|---|---|---|---|---|
| Bored tunnel utilising TBM | Yes | Mining and Hard rock (dolerite) should be avoided | Effects limited to portal areas and work site away from river. Waste disposal to be evaluated | No, separate tunnel required | Primary method for Forth Crossing Tunnel |
| Immersed Tube | Yes | Hard rock in tunnel horizon costly and should be avoided | Direct and indirect effects on SPA and SSSI likely | Yes | Only considered in combination with a TBM in corridor E |
| Cut and Cover | Yes, only on land, inter-tidal and shallow water | Hard rock undesirable as may require blasting | Local effects on land, direct and indirect effects on SPA and SSSI if used in or adjacent to river | Yes | Approaches to TBM tunnel |
| Mining | Yes, in coal measures and dolerites, not in sand and gravels under river | Competent ground and manageable groundwater pressure required, or extensive ground treatment likely | Effects limited to portals or shafts and associated work sites. Effects from blasting vibration (if used) | Yes, but unlikely to be economic | Shafts, ventilation and cross passage construction |