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# Independent Review of a Tunnel Connection to Vestmannaeyjar

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# 1 Introduction

In January 2000 a report was produced by the Public Roads Administration, which studied potential construction methods and associated costs for providing a road tunnel connection between Vestmannaeyjar and mainland Iceland. The Islands are home to a population of approximately 5000, and the main island of Heimaey is approximately 10km offshore of the mainland.

The 2000 report identified three potential methods of forming the tunnel, by conventional drill-and-blast techniques through the deep bedrock, by immersed tunnel, and by using the untried submerged floating tube method. The tunnels proposed in the report ranged between 18.5km and 26km in total length, and the cost estimates for the construction of the tunnel ranged from 20 – 35 billion ISK for the drill-and-blast method, to 120 – 150 billion ISK for the submerged floating tube tunnel.

It has been recognized that the technological advances made in tunnelling methods in recent years have resulted in an effective reduction in cost of tunnel construction. Also, the latest tunnelling work that is being carried out in Iceland, for the Kárahnjúkar Hydroelectric Project is utilising tunnel boring machines for the long tunnel drives, as the contractor sees this to be the most cost-effective form of construction. The 2000 study did not address Tunnel Boring Machines in the report. As a result, the Public Roads Administration has commissioned Mott MacDonald and Línuhönnun to conduct an independent study of the construction methods and costs of forming a fixed link between Vestmannaeyjar and the mainland.

Mott MacDonald is one of the world's largest multi-disciplinary engineering consultancies, with over 7000 staff employed in over 50 countries. The firm was founded on transportation projects, and has been associated with the majority of the highway tunnels built in the UK throughout the last century. The Group has unrivalled experience with the design of major undersea tunnels, with the Channel Tunnel between UK and France, the Storebaelt Rail Tunnels in Denmark, Sydney Harbour Tunnel, Hong Kong SSDS and several cable tunnels in Singapore being the leading projects. The expertise of Mott MacDonald's staff encompass the design and implementation of the full range of tunnel construction methods, including bored tunnels in soft ground and hard rock, drill and blast techniques, and immersed tube techniques for sub-aqueous tunnels.

In terms of the fire and life safety issues relating to transportation projects, the company authored the UK guide "Design of Road Tunnels" (BD78/99). In the wake of the various serious tunnel fire incidents in recent years, Mott MacDonald has monitored and contributed to the subsequent debate through representation on the PIARC Tunnels Technical Committee and four of the six working groups which support it. Currently the Group is teamed with Línuhönnun in the supervision of construction of the tunnelling for the Kárahnjúkar Hydroelectric project.

Mott MacDonald's worldwide database of tunnelling experience together with Línuhönnun's local knowledge of geology and local practices has been combined to produce this independent study into the feasibility and cost of a fixed link between Vestmannaeyjar and the mainland. This new study investigates the alignments that were previously proposed, together with the application of tunnel boring machines that could be used in the shallower soft ground under the sea bed as well as the deep hard rock.

In determining the feasibility of the crossing, great emphasis has been placed on understanding the needs and requirements of all current standards for road tunnels in terms of fire and life safety. The layout of new and planned road tunnels in terms of escape provisions and monitoring equipment is continually evolving. Existing facilities throughout Europe are also being upgraded, often at considerable cost. Any proposed road tunnel to Vestmannaeyjar would need to be designed and constructed in accordance with all applicable legislation, and all the features required by such legislation are identified and accounted for in the cost estimates.

# 2 Review of Previous Study

The Preliminary Study into the Vestmannaeyjar Road Connection was produced by the Public Roads Administration in January 2000. The report looked extensively into three separate methods of forming the tunnel to the mainland: i) a conventional mined tunnel through the rock horizon; ii) an immersed tube tunnel located in the soft sediments of the sea bed; and iii) a submerged floating tube which is located above the sea bed.

An extensive assessment study was conducted for the report which looked into the Natural Conditions of the area, and this addressed the geography, sea conditions and bathymetry, and presented a detailed appraisal of the geology – including the volcanic and seismic nature of the subject area.

The island of Heimaey is located approximately 10km off the southern shoreline of the mainland. A deep channel, Áll, which attains depths of over 90 metres exists in the sea bed directly north of the island, and this acts as a major barrier in forming a tunnel directly between Heimaey and the mainland. The level of the bedrock is very deep, up to 200 metres below sea level, and on the mainland the minimum thickness of the overlying sand horizons in the Landeyjasandur area is 40 – 50 metres near the farm Kross. The area is a volcanic system in its early stages and therefore active volcanically, which is a major concern for any construction activity, only 31 year ago in 1973 a volcanic eruption started on the main Island itself. Seismically it was considered in the report that the area from Landeyjar and out beyond Vestmannaeyjar lies outside the main earthquake zones, so that large earthquakes epicentres in this area are rare. However, there remains considerable seismic activity around the islands, which is generally linked to volcanic eruptions or magma movements. Again, such issues would impact on the design and construction of a tunnel.

As mentioned previously, three separate forms of tunnel construction were addressed in the report. Given the extreme depths of the seabed and the lengths of the tunnels involved, it is agreed that the conventional tunnelling method will be significantly cheaper than both the immersed tunnel and the submerged floating tube methods. From previous Mott MacDonald experience in comparative studies of bored and immersed tube tunnels, the conventional construction method becomes more cost-effective for a single bore tunnel after a length of approximately 2km. The 12.5km of tunnel required for the Vestmannaeyjar tunnel, as well as the extreme sea conditions, would rule out the viability of the immersed tunnel option. Although a number of submerged floating tubes are being proposed around the world, none have been constructed to date. When the first such tube is constructed it will be located in far calmer waters than the channel between Vestmannaeyjar and the mainland. Thus the submerged floating tube method is not considered appropriate for the crossing and has not been studied further in this latest report.

The conventional mined tunnel considered in the previous report would be formed by drill-and-blast methods and as such would be located entirely within the hard rock horizon. This meant that the tunnel would be 200 – 300 metres deep under the sea. Two alignment options were considered in the study: the first option connected Heimaey with the Landeyjar area, giving a tunnel length of 18km; the second option continued through to Highway 1 at the Eyjafjöll mountains, with a total tunnel length of 26km.

The report concluded that the shorter tunnel was the most feasible of the two options. However, the level of the rock in the Landeyjar area is approximately 40 – 50 metres below the surface level, so a significant entrance ramp of 800 metres in length, accommodating an approach road of 7% gradient would be required. The tunnel would be a single bore with a cross section of approximately 50m$^2$ accommodating two lanes of traffic operating in a bi-directional manner. Safety lay-bys would probably need to be incorporated into the tunnel at discrete locations.

The tunnel portal on Heimaey would be located in the south part of Há, which is approximately 1 km from where the alignment crosses the shoreline. The approach to the tunnel portal on Heimaey would be limited to a shallow gradient. Including the approach structures, the overall tunnel length would be approximately 18.5km, making it the second longest road tunnel in the world, and the longest sub-sea road tunnel.

An additional 12 km of surface road would be necessary on the mainland to connect the tunnel to Highway 1, and this was included in the overall cost of the project, which was estimated at 20 - 25 billion ISK. The project would take an estimated 6 – 7 years to complete.

A number of uncertainties and risks were identified in the study. The majority of these risks related to the ground conditions and it was recognised that limited knowledge was available on the type, quality and depth of the bedrock, particularly under the sea. There also exists the risks of volcanic and seismic activity, and subsequent events such as floods emanating from the glaciers. It was considered that any continuation of the preliminary study should focus on the volcanism of the area and the fault zone in All, and to improve the geotechnical data along the proposed tunnel alignment.

# 3 Geological and Geotechnical Conditions

## 3.1 Introduction

The Vestmannaeyjar archipelago is a cluster of volcanic islands formed by sub-marine or sub-glacial eruptions. The largest island, Heimaey, represents the centre of a volcanic system in its early evolution. The system is very young, as the first formations are of late Pleistocene age (Weichsel). The Vestmannaeyjar volcanic system can be regarded as the youngest and southernmost part of the Eastern Volcanic Zone. The current understanding of the rift system through Iceland is that the Islands form the tip of a propagating rift zone. The Eastern Volcanic Zone is extending southwards, by fracturing through series of Tertiary rock formations primarily formed in the Western Volcanic Zone. Among others, Mattsson and Höskuldsson (2003) have suggested that it is likely that Heimaey will, with increased volcanic activity, develop into a central volcano like the mature volcanic centres situated on the Icelandic mainland.

Investigations have been carried out on the Vestmannaeyjar volcanic system since the late 19th century, but enhanced greatly when the Surtsey eruption demonstrated the behaviour of a sub-marine eruption so elegantly to the world. Numerous articles, books and theses have been published so far. Most of these concentrate on the volcanic activity and the geological history of the Island. Broadly these can be classified as 6 different phases:

1. Studies carried out prior to the Surtsey eruption (late 19th century to 1960) led by Þorvaldur Thorodsen, Trausti Einarsson and Guðmundur Kjartansson.

2. The Surtsey eruption and Heimaey deep drilling 1965. Led by Sigurður Þórarinsson, Guðmundur Pálmason and others.

3. Geological investigations on Heimaey, Surtsey and the Vestmannaeyjar volcanic system led by Sveinn P. Jakobsson.

4. Hreinn Haraldsson and Hans Palm, carried out geophysical studies on Markarfljótssandur in the late 1970s and early 1980s.

5. Sub-sea geophysical studies by the Marine Research Institute near Vestmannaeyjar in the 1980s.

6. Marine geophysical investigations carried out in 2003 (Höskuldsson 2003), associated with geological investigation on Heimaey by Mattson and Höskuldsson.

The first three cover the surface geology and volcanic history of Surtsey and Heimaey, along with detailed information on the foundation of Heimaey. Around the island there are many sub-marine eruptive vents, suggesting quite active environment in the Vestmannaeyjar system. Haraldsson and Palm along with other older onshore geophysical investigations give details of the portal conditions in the alluvial formation of Landeyjasandur.

The last two points cover marine investigations in the actual tunnel area between the Islands and the mainland. The last and most recent investigation focused on the seafloor mainly with detailed bathymetrical mapping and high frequency seismic studies. These do not have the penetration to investigate the bedrock in any details with regards to tunnelling properties of the rock, but on the other hand they do penetrate the soft sediments with quite high resolution. The main objective of those investigations has been the volcanic and tectonic history and evolution of the Vestmannaeyjar volcanic system in general. The only investigations that give some idea about tunnelling conditions along possible alignments are the investigation carried out by the Marine Institute in the 1980s.

## 3.2 Geological Setting of Project Area

The foundation of the main island, Heimaey along with large parts of that island is comprised of moberg formations (hyaloclastite), along with lava and shallow intrusion. In 1964 a deep borehole was drilled on Heimaey. From this drill hole the stratigraphy of Heimaey is revealed the volcanic formation of Heimaey extends down to a depth of 180 m. Two layers of tillite are found at 94-104 m and 160-168 m in depth. Below the volcanic formation is an approximately 650 m thick mass of marine sediments. Underneath the sediments are basalt lava layers most likely of Tertiary age, which extend to the bottom of the hole at 1565 m.

Haraldson and Palm (1980) carried out geophysical investigations on the alluvium formation of Landeyjarsandur in the late 1970s. Seismic refraction surveys were carried out: prior to that other investigation teams had conducted seismic reflection and resitivity measurements. These surveys indicated that the sandur formation is generally quite thick. The shallowest depth to bedrock was found near the farm Kross, where the depth to bedrock is expected to be at 40-50 m. From there the depth increases significantly toward the east, reaching up to 250 m near Bakki. Apparently a glacially eroded valley is running from the Markarfljót - Bakki area south east into Háfadjúp. Onshore no bedrock is found at reasonably shallow depths until the vicinity of Eyjafjöll central volcano is reached. The bedrock below the sand appears to be of two kinds: moberg formation from the Quaternary period and older basalt layers, even from the Tertiary period. Moberg formation is used in this context as a synonym for hyaloclastite volcanic rock from the Quaternary period, which can include tuff, breccia, pillow lava and occasional layers of lava as well as sedimentary rock from the Ice Age and/or a combination of all these.

It has been pointed out some concern that there is a drop in the elevation of the lava bedrock formations between the onshore measurements and the deep borehole on Heimaey. A drop of approximately 600 m in elevation of what is believed to be similar formations is observed. It has been suggested that "Áll", an east – west oriented trench in the middle of the strait between the mainland and the Heimaey, is in some way responsible for this drop. However, Höskuldsson has pointed out that this elevation drop may be explained simply with the dipping of the observed lava formation. The distance between the two observation points is about 18 km, thus the observed drop in elevation equals a dip of about 4°. Such a dip is not uncommon within the Tertiary lava pile. Thus the observed drop does not need any fault since it is not sudden but graduate.

In 1980 and 1983 the Marine Research Institute performed seismic reflection surveys around Vestmannaeyjar (Thors & Helgason 1988). Sparker equipment was used for the surveying, which is suitable for the upper layers (50 – 300 m) of the bedrock in shallow waters. Surveying lines were measured across the strait between the mainland and Heimaey both parallel and perpendicular to the east-west alignment of the strait. These are currently the only results that reveal some of the characteristics of the bedrock in the strait. The 2003 geophysical survey only covers the upper layers of the recent sediments and a detailed mapping of the sea floor. Those give valuable data for wider understanding of the volcanic history of the region.

As described earlier a deep trench or channel "Áll" runs east–west in the strait between Heimaey and the mainland. That channel marks a significant change in the bedrock. The seismic reflection surveys confirm that the moberg formation of Vestmannaeyjar extends towards "Áll", which marks the northern boarder of the Vestmannaeyjar formation. Minor volcanic eruption has been suggested on the north bank of Áll. Thus it can be regarded as the northern limits of the volcanic system. From the coastline a thick layer of recent sediments of Holocene age extends towards the north bank of the "Áll". This relatively abrupt change in both the current topography of the seafloor and the difference between geological formations is of concern and has to be firmly resolved before any decision on tunnelling in the area are made.

Pálmason et al. (1965), later supported by Kristjánsson (1976) suggested that a discontinuity in the bedrock extends through the channel in conjunction with linear formations discovered by magnetic anomaly measurement on the shelf south of Iceland. This linear formation lines up with the channel "Áll". Thors & Helgason (1988) assume that the Heimaey formation is resting on thick marine sediments covering the lava bedrock. On the top of these sediments are tillite layers observed in the borehole on Heimaey. Thors & Helgason suggest that these tillite layers fit with strong reflections below the Holocene sediments on the northern bank of Áll. From the shoreline south towards Áll are thick sediments belonging to delta formations that can be related to the relatively recent (Holocene) alluvial formations along the coastline.

The latest marine investigation carried out in the summer of 2003 along with detailed geological mapping of Heimaey has modified the geological ideas of the Áll area to a certain extent. Firstly Mattsson and Höskuldsson (2003) conclude that the oldest surface formations in Heimaey date back to early Holocene, approximately 9500 years, based on the sub-aerial nature of the volcanics. The Norðurklettar formation might have formed during a 500 years. Hey et al. (2003) and Höskuldsson et al. (2003) whose ideas are based on the marine investigations from 2003, argue that Vestmannaeyjar acted as Nunatak during the last glacial period, diverting the glacial tongue south east into Háfadjúp and south west of the Islands. Thus Vestmannaeyjar being a dry land during that time thus extending again the timeframe of the volcanism on Heimaey.

Harðarson and Haraldsson (2000) and Imsland (1999) discuss the possibility that Áll maybe a tectonically active feature, which may explain the large vertical displacement across the channel. Based on the 2003 investigations Hey et al. (2003) and Höskuldsson et al. (2003) suggests that the southern bank of Áll has been shaped by glacial erosion and the northern bank formed by the Holocene delta formation progressing from the north as suggested earlier. The findings of the same investigation, that are based on high frequency seismic profiles across Áll, show that no tectonic movements have taken place during Holocene time on a suspected fault zone running along Áll.

This matter has been turned into one of the focal points in the discussion of potential tunnelling conditions in that area. With regards to that, these latest investigations do in deed provide a different explanation of the formation and existence of the channel in Áll. But as that can not be considered conclusive, this matter is still considered to be subject to discussion. Despite the fact that information on the bedrock properties is very limited it can nevertheless be expected that tunnelling conditions on any alignment between the mainland and Vestmannaeyjar will be very demanding and cannot be directly compared to the ongoing tunnelling projects in Iceland.

## 3.3 Volcanic Activity

Eruptive fissures running in a SW-NE direction have piled up the Vestmannaeyjar volcanic ridge. The largest and latest volcanic eruptions in historical times in the area are the Surtsey eruption (1963-1967) and the Heimaey eruption (1973). During the Surtsey eruption, at least six volcanic fissures opened on a 5 km long echelon pattern. The Heimaey eruption included both eruption on land and sub-marine eruption, just offshore Heimaey, along the 3.5 km long volcanic fissure in Eldfell. It is further believed that a small eruption occurred in May 1973 at the southern edge of Áll, 6 km from Heimaey, close to the water pipeline (Þórarinsson 1977).

Sea charts show a number of hills and mounds rising up from the ocean floor on the shelf around Vestmannaeyjar, without reaching the sea surface. Geophysical investigations also show a number of hills buried in the sediments. The foundation of Heimaey dates from the beginning of local volcanism in the Heimaey area. Heimaey has probably been active for the entire time that volcanic activity has proceeded in the Vestmannaeyjar system. Activity on the outer islands and around Heimaey seems to have shifted between areas (Thors & Helgason 1988). About 70-80 volcanoes have been identified in the volcanic system of Vestmannaeyjar. There are 17 islands in the archipelago with at least 22 known Holocene sub-aerial volcanic sites, the rest are from the final phase of the Ice Age (Jakobsson 1982).

The oldest surface formations of Heimaey are the northern parts Heimaklettur and Ystiklettur, and to the south Sæfjall (5470 BP) and Stórhöfði (~6000 BP). Some 5000-6000 years ago Heimaey was probably two separate islands that then were joined by an eruption forming Helgafell that connected the islands. It has been suggested that the southern parts of Heimaey, Elliðaey and Bjarnarey are all around 5000-6000 years old. Little else is known with any certainty regarding the age of Vestmannaeyjar or of the bedrock between the mainland and the Islands. Information from the deep borehole on Heimaey indicates that the Islands started to pile up during the late pleistocene. Thors & Helgason (1988) have suggested a maximum age of the Vestmannaeyjar volcanic system to be about 70,000 years. Jakobsson (1982) has suggested that the production of volcanic material started 80-120,000 years ago.

## 3.4 Earthquake Activity

The area south from Landeyjar, out past Vestmannaeyjar, lies outside the main earthquake epicentre zones in Iceland. Therefore the possibility of major earthquakes originating in this region is low. Nevertheless there is considerable seismic activity around the Islands, involving activity connected to volcanic eruptions and magma movements. Earthquakes in relation with volcanic eruptions are generally small with the strongest peaks in the beginning.

Lateral movement of the plate boundaries is transformed from the Eastern Volcanic Zone to the Western Volcanic Zone over the South Iceland Seismic Zone, which extends from Hveragerði in west to Hekla in east. The strongest earthquakes in this area occur in this zone, which is among the most active earthquake zones in Iceland. The perimeter of this zone is about 50 km northwest of Vestmannaeyjar. The latest large earthquakes to occur in this zone were in 1896, 1912 and 2000.

As the area between the mainland and Vestmannaeyjar lies outside the fracture zone, the impact of earthquakes in the area is limited to wave motion. It is unlikely that lateral displacement will take place near the Islands. It has been suggested though that the Áll represents an active fracture zone (Harðarson & Haraldsson 2000) and that southward propagating rift may induce earthquakes within the Islands vicinity. However the latest investigations from the summer of 2003 show that no neo-tectonic movements can be identified within the Holocene sediments between Heimaey and the mainland. The results are somewhat preliminary and do not cover the whole area (Höskuldsson 2003).

However one cannot rule out the possibility of lateral movements within the Vestmannaeyjar system caused by the propagating rift or magma intrusion in the area. But regarding the propagating rift theory then it is clear that the rift related tectonics in the area would continue along the northeast – southwest lineament. On the other hand time scale her is large, on the order of million of years. Lateral ground movements crossing tunnel alignments will definitely have devastating effects on the structure.

Experiences from both Ólafsfjarðarmúli and Hvalfjörður tunnels have shown that earthquake waves have little effects on the tunnels within rock. With regard to the potential Vestmannaeyjar tunnel, earthquake acceleration on the proposed portal in the deep and water saturated alluvium of Landeyjar may cause a significant strain on the portal excavation.

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# 4 Design Parameters

## 4.1 Introduction

In the preparation of an independent cost estimate for the Vestmannaeyjar tunnel project it will be necessary to fully understand the type and size of tunnel that needs to be constructed, and the installations that are required by current, and future, legislation. The project will involve a significant length of undersea tunnel, with little or no potential for intermediate means of escape from the tunnel. It is recognised that safety is always of paramount importance in both the construction and operation of transportation tunnels, and that all the features required by legislation are identified and accounted for in the cost estimates.

The following sections present a review of design standards and legislation that is in place with regard to the construction of a new undersea tunnel. A number of design standards have been studied, including those of Iceland, Norway and the EU. Although Norway is not a member of the European Union it should be noted that that country is about to embark on an assessment and upgrading program for all of its road tunnels to bring the safety standards in line with EU regulations. Therefore it is considered that the codes and practices of the EU should be adopted during the planning for any major road tunnel in Iceland.

## 4.2 Existing Road Runnels in Iceland

This summary looks at physical characteristics of existing road tunnels in Iceland and compares them with the requirements for existing and new road tunnels as laid down EU regulation 16215/03.

Until recently Iceland contained only a very small total length of road tunnels, approximately 4.9 km in 1991, all of which had very low annual average daily traffic (AADT) flows of less than 300 vehicles. Since then there has been considerable investment in the design and construction of new tunnels, notably the Hvalfjörður tunnel north east of Reykjavik.

### 4.2.1 Hvalfjörður Tunnel

The Hvalfjörður Tunnel is a 5.8 km long single bore drill-and-blast tunnel with two different cross sections:

1. Cross section of $60m^2$; two lanes (T8.5); 3.6 km long; gradients of 7% and 4.4%

2. Cross section of $80m^2$; three lanes (T11); 2.2 km long; gradient of 8%

The tunnel safety installations were designed according to Norwegian requirements for a tunnel with a safety class of B (AADT less than 3500 vehicles within 20 years). It also complies with many of the clauses in EU regulation 16215/03.

The main principle for evacuation of a low traffic tunnel is to stop, turn around and escape in ones own vehicle. Therefore, turning niches are provided every 500 m. Battery powered emergency lighting is provided, along with fire extinguishers every 250 m and emergency telephones every 500 m. The traffic volume in 2003 was 3500 AADT.

### 4.2.2 Breiðadals and Botnsheiði Tunnel

The total length of tunnel is approximately 9100m with an intersection in the rock. 2.2km of the tunnel is double lane, 7.5m wide with a cross-section of 48.5m². The rest is single lane, 5m wide and 29.5m² in cross-section, with recesses approximately that are160m apart, 32m long, 8m wide, with a cross-section of 50.8m². Gradients in the tunnel do not exceed 1.5% and are often lower.

All rock is supported with rock bolts and sprayed concrete. Protection from water and frost consists of a polyethylene foam sheet secured to the surface with rock bolts and steel bands, partly covered with shotcrete. The traffic volume is 270 and 480 AADT in the two different single lane sections and 670 AADT in the double lane section.

### 4.2.3 Arnardalshamar Tunnel

The Arnardalshamar tunnel is only 30 m long, with a cross-section of approximately 50m² after a recent widening. No problems have been experienced with a traffic volume of only 210 AADT.

### 4.2.4 Strákagöng Tunnel

At 800 m long this 21 m² single lane tunnel has four 25 m long recesses built into it. Twenty percent is supported with cast concrete and large numbers of rock bolts. The traffic level is only 260 AADT.

### 4.2.5 Oddsskarð Tunnel

The Oddsskarð Tunnel is 640 m long with a 24 m² cross-sectional area and has three recesses built into it. The tunnel is mainly supported with steel ribs and rock bolts, with about 50m sprayed concrete. The traffic level is 240 AADT.

### 4.2.6 Ólafsfjarðarmúli Tunnel

At 3400 long this 25m² single lane tunnel has 19, 43m², 32 m long recesses built into it. The tunnel was constructed using drill-and-blast and is lined with rock bolts and sprayed concrete. The traffic level is 420 AADT.

### 4.2.7 Compliance with EU Regulations

All of the road tunnels mentioned above with the exception of the Hvalfjörður tunnel fail to comply with EU safety standards as set down in the EU document 16215/03 'Proposal for a Directive of the European Parliament and the Council of Europe on minimum safety requirements for tunnels in the Trans-European Road Network – General Approach'. However due to either their length or traffic flows and in some cases a combination of both, compliance with the full standards is unnecessary and expensive.

## 4.3 European Union Regulations Regarding Long Road Tunnels

The following points are derived from a Proposal for a Directive of the European Parliament and of the Council on 'Minimum Safety Requirements for Tunnels in the Trans-European Road Network', Document 16215/03 ADD 1.

It should be noted that the directive declares "Member States are encouraged to develop national provisions aiming at a higher tunnel safety level." than the minimum level set down in the directive.

### 4.3.1 Safety Parameters

The following parameters shall be taken into account:

- tunnel length
- number of tubes
- number of lanes
- cross-sectional geometry
- vertical and horizontal alignment
- type of construction
- uni-directional or bi-directional traffic
- traffic volume per tube (including its time distribution)
- risk of congestion (daily or seasonal)
- access time of the emergency services
- presence and percentage of heavy goods vehicles
- presence, percentage and type of dangerous goods traffic
- characteristics of the access roads
- lane width
- speed considerations
- geographical and meteorological environment

The directive also requires the designation of an Administrative Authority, Tunnel Manager and Safety Officer.

*Clause 1.3 Traffic Volume*

Where the number of heavy goods vehicles over 3.5t exceeds 15% of the annual average daily traffic, or a seasonal daily traffic significantly exceeds the annual average daily traffic, the additional risk will be assessed and taken into account by increasing the traffic volume of the tunnel.

*Clause 2.1 Number of Tubes*

A twin-tube tunnel is only required where a 15-year forecast shows that the traffic volume will exceed 10000 vehicles per day and per lane. It is evident that in any tunnel constructed between the mainland and Heimaey would not have a traffic level exceeding this value, thus a single tube tunnel is adequate.

*Clause 2.2 Tunnel Geometry*

Longitudinal gradients above 5% shall not be permitted in new tunnels, unless no other solution is geographically possible. In tunnels with gradients higher than 3%, additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis.

*Clause 2.3 Escape Routes and Emergency Exits*

In tunnels without an emergency lane, emergency walkways, elevated or not, to be used by tunnel users in case of a breakdown or an accident shall be provided. Emergency exits allow tunnel users to leave the tunnel without their vehicles and reach a safe place in case of accident or a fire. Emergency exits shall be provided if an analysis of relevant risks including the smoke extension and spreading velocity under local conditions shows that the ventilation and other safety provisions are insufficient to ensure the safety of road users. In any case, in new tunnels, emergency exits shall be provided where the traffic volume is higher than 2000 vehicles per lane.

*Clause 2.5 Lay-bys*

For new bi-directional tunnels longer than 1500m where traffic volume is higher than 2000 vehicles per lane, lay-bys containing an emergency station shall be provided at distances which do not exceed 1000m, if emergency lanes are not foreseen.

*Clause 2.6 Drainage*

Where the transport of flammable and toxic liquids is permitted a drainage system shall be designed to prevent the spread of fire and toxic liquids through the tunnel.

*Clause 2.7 Fire Resistance*

Sufficient fire resistance must be provided in tunnels where a collapse can have catastrophic consequences.

*Clause 2.9 Ventilation*

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 the pollutants emitted by road vehicles in case the traffic is stopped due to an incident or an accident
- the control of heat and smoke in case of a fire.

A mechanical ventilation system must be installed in all tunnels over 1000m

*Clause 2.14 Monitoring systems*

Automatic fire detection systems shall be installed in all tunnels which do not have a control centre.

*Clause 2.15 Equipment to close the tunnel*

In all tunnels longer than 1000m, traffic signals shall be installed before the entrances so that the tunnel can be closed in case of an emergency. Additional means, such as variable message signs and barriers, can be provided to ensure appropriate obedience.

*Clause 2.17 Power Supply*

All tunnels shall have an emergency power supply able to ensure the functioning of safety equipment which is indispensable for the evacuation until all users have evacuated the tunnel. Electrical, measurement and control circuits shall be designed in such a way that a local failure, such as that due to a fire, does not affect unimpaired circuits.

## 4.4 Escape Frequency

### 4.4.1 Fire Safety Engineering Principles

To allow the application of fire safety engineering principles a number of assumptions need to be made such as:

- The rate of life threatening fire spread from when the incident first causes tunnel traffic to stop
- The response time of tunnel operators
- The response time of tunnel users
- The speed at which tunnel users can access an escape to a place of safety
- Passenger density and distribution along the tunnel
- Location of the fire
- The in-tunnel facilities which will influence the above times such as public address, emergency signage, facilities for the non-ambulant disabled etc.

### 4.4.2 International Standards Recommendations

International standards for road tunnels specify escape frequency for new construction. The best known standards in English are the UK standard BD78/99 Design of Road Tunnels and the United States document, NFPA502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2001 Edition. The European Parliament has issued; Proposal for a Directive of the European Parliament Council on minimum safety requirements for tunnels in the Trans-European Road Network. This standard states that the distance between two emergency exits shall not exceed 500m. However emergency exits do not need to be provided where the traffic volume is less than 2000 vehicles per lane and smoke extension and spreading velocity under local conditions shows that ventilation and other safety provisions are sufficient to ensure the safety of road users. Escape frequencies based on various prescriptive standards are defined in Table 4.1 over.

| Table 4.1: Standards on Escape Frequency | | | |
|---|---|---|---|
| **Ref. No.** | **Standard [date]** | **Escape frequency [clause]** | **Comment** |
| **1** | BD78/99 [1999] | 100m [3.16] | stated for twin bores |
| **2** | NFPA 502 [2001] | 300m [7.16.6]<br>200m [7.16.7 (1)] | 7.16.6 required for emergency exits<br>7.16.7 (1) required for cross-passages in twin bores |
| **3** | Proposal for EC Directive [2002] | ≤ 500m [1.5.1] | |
| **4** | CETU, France [2000] | 200m [2.2] | for urban tunnels |
| **5** | RABT, Germany [2002] | 300m [2.5.1.3] | |

## 4.5 Ventilation

### 4.5.1 Ventilation Design Assumptions

The preliminary ventilation design of the Vestmannaeyjar tunnel has been based on the following assumptions:

1. Likely peak traffic flow of 35 vehicles per hour, per direction (500 vehicles/day)
2. Conservative standard for vehicle emissions (EURO 2)
3. 15% of vehicle are taken to be trucks
4. Fire size of 30 MW
5. Traffic speed limit of 80 km/h

### 4.5.2 Proposed Allowable Pollution Levels

The proposed pollution levels have been based on the requirements of PIARC 2004, PIARC document “Pollution by Nitrogen Dioxide in Road Tunnels” (1999) and the British Highways Agency standard for tunnels, BD78/99. These proposed levels are given in Table 4.2.

| Table 4.2: Pollution level limits proposed for the Vestmannaeyjar tunnel | | | | |
|---|---|---|---|---|
| **Pollutant** | **Limits in normal traffic operations** | **Limits in congested traffic operations** | **Levels above which the tunnel should be closed** | **Levels during maintenance activities** |
| **Carbon monoxide (CO)** | 50 ppm peak | 50 ppm peak | 200 ppm peak | 30 ppm peak |
| **Nitrogen dioxide ($NO_2$)** | 1 ppm mean | 1 ppm mean | 5 ppm mean | 1 ppm peak |
| **Visible range** | 0.005 $m^{-1}$ peak | 0.005 $m^{-1}$ peak | 0.012 $m^{-1}$ peak | 0.003 $m^{-1}$ peak |

The limits in normal operations apply when traffic is freely flowing through the tunnel at full speed (80 km/h). If a traffic jam occurs and pollution levels start to rise at that point, the limits for congested traffic operations should be aimed at. In practice, this allows the visibility level to be worse, while levels for the other pollutants are unchanged.

In the unlikely event that the closure levels are reached, the tunnel should be closed and the cause of the high pollution levels investigated.

In a tunnel of this length and low usage, it is almost certain that maintenance crews will be present in the tunnel at the same time as traffic is travelling through. In order to ensure their health is not affected by the air quality within the tunnel, pollution levels must be kept below stricter guidelines for the duration of the maintenance activity.

The level of nitrogen dioxide ($NO_2$) has been assumed to be one-fifth of the level of oxides of nitrogen ($NO_X$), i.e. a volumetric conversion rate of 20%. This is a conservative estimate; the usual recommended figure is 10%. A figure of 20% has been selected because PIARC indicates that the conversion rate can double during periods of light-traffic/low emissions: these conditions will be present most of the time in the Vestmannaeyjar tunnel.

### 4.5.3 Design Solution - Pollution Control

Ventilation for the Vestmannaeyjar tunnel can be made to work with a longitudinal system employing jet fans to move the air from portal to portal. There is no need to provide ventilation shafts to ventilate the tunnel.

This is mostly because the traffic flow through the tunnel is so light. The airflow induced by traffic is low, but so is the amount of pollutants emitted by the vehicles.

The air in the tunnel will be pushed east and west by the action of traffic, which will keep the air near the portals fairly clean while pollutants build up in the centre section of the tunnel. It is impossible to predict how far the polluted centre section will actually extend, but studies show that the air in the tunnel can be kept clean using the jet fans to change the air within the tunnel at regular intervals. This could be carried out once a night, as the pollutants emitted by the vehicles will not be enough to raise the pollution levels above the allowable levels in the course of the next day.

### 4.5.4 Design Solution – Smoke Control and Fire/Life Safety

There will be so few occupants in the Vestmannaeyjar tunnel that a longitudinal ventilation system is proposed, in conjunction with a pressurized escape route in the tunnel invert.

The longitudinal system will blow smoke from a burning vehicle to one side of the fire. Any vehicles behind the fire will be kept in clean air, although the low traffic flow through the tunnel makes it likely there will be no more than a few vehicles there. Vehicles coming towards the site of the fire in the other direction will find the tunnel filled with smoke. They will be given a choice of performing a three-point turn to go back the way they came, or stopping their vehicles then escaping into the gallery below the carriageway.

### 4.5.5 Operational Structure and Emergency Services

The operational philosophy for the tunnel will need to be considered carefully.

- All vehicles entering the tunnel should be counted in and out, so the number in the tunnel at any one time is known.

- All people going into the tunnel should be informed of its unusual nature and advised how to behave during incidents.

There is a discussion to be had over whether the tunnel needs to be continuously monitored. If it is not, then a decision needs to be made on how complex the control system will be: the simpler it is, the more likely it is to make a wrong decision in a minority of incident cases. The more complex it is, the more likely it is that those involved in responding to the incidents will fail to predict what the control system will do.

The recommended operational structure is to have a very simple automatic control system. This will operate tunnel lighting in response to photometers, pollution control in response to pollution sensors (possibly a timer as well). The incident ventilation system will be as simple as possible, blowing air (and hence smoke) one way in response to a fire alarm. If the only local fire brigade are located on Heimaey, it would make sense to choose to blow the smoke towards the mainland, so that the Heimaey emergency services have a path in clear air to the site of the incident.

This recommendation is based on what little information is available to date and should be reviewed when more information is available. It may be that continuous monitoring of the tunnel is practicable.

### 4.5.6 Psychological Effects

The monotony of driving along such a long tunnel needs to be taken into account in its design. The horizontal alignment needs to be broken up into a series of curved and straight sections, and the overall alignment should be such as to maintain long sightlines, preferably of the order of a kilometre.

The tunnel lining will need to have frequent changes of colour scheme so as to change the drivers' perception of the environment. It would also be necessary to increase the lighting levels in the interior zone at intervals to get the attention of the driver.

The tunnel cross-section also has an impact on the comfort of drivers. A wide verge next to the carriageway is a benefit, as drivers will not feel cramped by the nearness of the sidewall but comes at high cost, as it increases the width of the tunnel.

## 4.6 Geometry

### 4.6.1 Geometry for a Bi-Directional Tunnel

This report investigates a number of tunnelling concepts, the cross sections for which are included in Appendix B at the end of this report. Each of these basic concepts assumes a single bore, bi-directional traffic flow. The size of the tunnel is determined by the clearance space required for the types of vehicles and the number of traffic lanes. Table 4.3 below shows current international practice for the widths traffic lanes, carriageways and maintained headroom.

Currently no European Standard exists on cross section geometry in road tunnels. Norwegian standards require a minimum carriageway width narrower than any other in Europe, only 7.0m for a design speed of 80-100km/h, whilst the Swiss specify a 7.75m carriageway width for a design speed of 80 – 120km/h. More common are carriageway widths of around 7m, as in the Hvalfjörður Tunnel.

Any tunnel between the mainland and Heimaey would be single bore, bi-directional. A carriageway width of 7m with 1m wide walkways each side is considered adequate, giving a minimum total deck width of 9m. The maintained headroom would need to be 4.60m with an additional 0.10m safety zone, making the total headroom 4.70m. This would ensure that the Vestmannaeyjar tunnel is in line with other European tunnels.

| Table 4.3: Current International Practice for Traffic Lane Width and Headroom | | | | |
|---|---|---|---|---|
| **Country and Name of Guidelines or Other Source** | **Design or Reference Speed** | **Width of Carriageway** | **Maintained Headroom** | **Safety Zone** |
| **Austria**<br>**RVS 9.232** | 80-100 | 7.00 | 4.70 | n.s. |
| **Denmark**<br>**(practice)** | 90-120 | 7.20 | 4.60 | 0.20 |
| **France**<br>**CETU** | 80-100 | 7.00 | 4.50 | 0.10 |
| **Germany**<br>**RAS-Q 1996** | 100<br>70 | 7.00<br>7.00 | 4.50 | n.s. |
| **Japan**<br>**Road Structure Ordnance** | 80-120<br>60 | 7.00<br>6.50 | 4.50 | n.s. |
| **The Netherlands**<br>**ROA** | 120<br>90 | 7.00<br>6.50 | 4.50 | 0.20 |
| **Norway (Håndbok 021)**<br>**Design Guide Road Tunnels** | 80-100 | 6.90 | 4.60 | 0.10 |
| **Spain**<br>**Instruction** | 90-120 | 7.00 | 5.00 | n.s. |
| **Sweden**<br>**Tunnel 99** | 70<br>90 | 7.00<br>7.50 | 4.50 | 0.20 |
| **Switzerland**<br>**SN 640201** | 80-120 | 7.75 | 4.50 | n.s. |
| **UK**<br>**TD27(DMRB 6.1.2)** | 110 | 7.30 | 5.35 | 0.25 |
| **USA**<br>**AASHTO** | | 7.20 | 4.90 | n.s. |

With the traffic envelope and carriageway width specified above a tunnel with an internal diameter of 10m is required. If the road deck is constructed out of pre-cast concrete segments it may be possible to utilise the tunnel invert, with a clearance of up to 2.8m. This amount of room would allow the invert to be used as means of escape in the event of an incident, although access from the road deck would prove troublesome.

## 4.7 Ground Movements

### 4.7.1 Earthquake Protection

The effects of earthquakes on underground structures may be broadly grouped into two general classes, shaking and faulting. In response to earthquake motion of bedrock the soil transmits energy by waves. Waves travelling at right angles to the structure will tend to move it back and forth longitudinally, and may tend to pull it loose at zones of abrupt transitions in geology. Faulting is primary shearing displacement of the bedrock and in general it is not feasible to design structures to resist major ground faulting.

Previous studies, state that the area around Vestmannaeyjar and Landeyjar is not within the main faulting zones in Iceland. However small earthquakes associated with volcanic eruptions and magma movements are common. There have also been a number of very strong earthquakes in the past and their occurrence again cannot be ruled out. Fortunately the impact of earthquakes is restricted to wave motion as there are no unconformities in the area, except possibly around the Áll. This existing information indicates that lateral displacement in any earthquake will be minimal.

The level of earthquake protection required depends heavily on the geology of the ground through which the tunnel runs and its stiffness relative to the tunnel lining. In hard rock the ground is generally considered to be stiffer than the tunnel lining, thus any earthquake is likely to have a minimal impact. However the sands of Landeyjarsandur and the sea bed may not be as stiff as the tunnel lining, and the impact of an earthquake on a tunnel within sand may be greater than the impact from an equivalent earthquake on a tunnel within rock.

It should be recognised that although the absolute amplitude of earthquake displacement may be large, this displacement is spread over a long length. The rate of earthquake distortion is generally small, and is often within the elastic deformation capacity of the structure. If it can be established that the maximum deformation imposed by the earthquake will not strain the tunnel beyond its elastic range then no further provisions to resist the deformation are required.

However, problems may occur where there is a change of geology or the stiffness of the tunnel changes, such as at a portal. The sands of the sea bed may move considerably more in an earthquake than the rock of Vestmannaeyjar so that any tunnel crossing the interface of these media will suffer disparate movement within each side of the interface. If movement joints are not built in it is possible that the tunnel will become misaligned, in a worst case resulting in failure of the lining, and at best expensive repairs. A similar problem may occur at the portals. The relatively stiff portal structures will suffer differential movements to the tunnel. Once again movement joints may have to be built in.

### 4.7.2 Settlement

The proposed tunnel alignments do not go underneath any areas where settlement may be a problem, such as other tunnels, buildings and transport corridors. As a result there will not have to be any remedial measures to ensure that no damage occurs to other property. This will have the benefit of significant risk reduction and cost savings in ground monitoring.

# 5 Layout of the Proposed Vestmannaeyjar Tunnel

## 5.1 Specific Local Considerations

Relevant conditions specific to the Vestmannaeyjar tunnel include:

1. The tunnel is bi-directional having one lane of traffic in each direction
2. The tunnel will probably be tolled at one of the entrances providing 24hour manning, thereby allowing excellent traffic control and rapid traffic incident response at the tolled end
3. Heavy goods vehicles (>3.5tonnes) are allowed
4. Hazardous goods may be allowed
5. Traffic is low predicted to be approximately 500 vehicles per day
6. Response time of local emergency and rescue service is likely to be slow

## 5.2 Safety in the Vestmannaeyjar Tunnel

Due to the length of any tunnel, the bi-directional traffic flow and remoteness of the area any safety provisions should be of a high standard. International standards do recognise that cost is an important factor and in low-traffic bi-directional tunnels, and in a tunnel such as that proposed it may not be economical to provide escapes every 100m. The cost of providing preventive measures such as tunnel-policing need to be weighed against that of providing escape facilities and the benefits of them. For this reason safety recommendations for the Vestmannaeyjar tunnel are as follows.

With the traffic level as low as that envisaged, emergency exits do not need to be provided. The most economical method of emergency egress will be for users to turn their vehicles around and escape. However a circular tunnel, such as that produced by a TBM will have space under the road deck, within the tunnel invert, that could be used for emergency escape, as is the case in Mersey Queensway Tunnel in Liverpool, England. The provision of emergency exits would be extremely beneficial to the tunnel safety, and access to the invert from the road deck could be provided at 250m intervals. Escapes should be of adequate width with step-free access for use by wheelchair-bound tunnel users. In an emergency, escapees should initially be able to begin making their own way out of the tunnel, making use of assistance when it arrives.

Emergency walkways, 1m wide with a height clearance of 2.3m should be provided on each side of the carriageway. Access to the invert may be provided from ramps off the walkway. Lay-bys are not required and will be very expensive to provide if an alignment is chosen that goes through the sand of the sea bed. However they will contribute significantly to the safety of the tunnel and it is recommended that they are provided at least every 1000m on the flat and shallow sections. On the steep climbing section within the rock up to Heimaey, lay-bys will be much cheaper and as such could be provided approximately every 250m.

Mechanical ventilation and fire suppression systems should be provided to control the spread of fire and smoke, with a control centre managing the tunnel systems, and monitoring traffic within the tunnel through CCTV.

## 5.3 Recommendations of Proposed Layout

*Number of Tubes*: A single bore bi-directional tunnel can be specified, as traffic volumes are not expected to exceed 250 vehicles/lane. If seasonal daily traffic is shown not to significantly exceed annual average daily traffic, and heavy goods vehicles over 3.5t do not exceed 15% the annual average daily traffic no additional risk assessments are required.

*Tunnel Geometry*: Gradients over 5% are not be permitted unless no other solution is geographically possible.

*Emergency Walkways*: Need to be provided as an emergency lane is not included.

*Emergency Exits*: Must allow users to exit the tunnel and should have no dead ends. These are recommended, as in the event of a fire smoke will be blown one way down the tunnel and users in the smoke filled parts of the tunnel may need an alternative, safe method of emergency egress.

*Lay-bys*: With the traffic level not expected to exceed 500 vehicles per day lay-bys are not compulsory. However as the tunnel is single lane bi-directional is probably advisable that they are provided at least every 1000m and contain emergency stations.

*Drainage*: If the transport of flammable and toxic liquids is to be allowed, there must be suitable drainage.

*Fire resistance*: The tunnel lining must be fire resistant where a collapse can have catastrophic consequences.

*Lighting*: Normal, emergency and evacuation lighting must be provided throughout the tunnel.

*Ventilation*: Mechanical ventilation is recommended due to the length of the tunnel.

*Emergency Stations*: Emergency stations with a telephone and 2 extinguishers must be provided every 150 m.

*Water Supply*: Fire Hydrants must be available every 250 m, possibly at the emergency stations.

*Monitoring Systems*: The construction of a control centre is recommended, requiring the installation of a video system within the tunnel. Automatic incident and fire detection systems should be in place.

*Equipment to close the tunnel*: Traffic signals must be in place at the entrance to the tunnel, possibly with the addition of a physical barrier to ensure compliance. It is recommended that traffic signals are placed every 1000m in the tunnel.

*Communications Systems*: Radio re-broadcasting for emergency services and the emergency radio messages for tunnels users are recommended, and are mandatory when a control centre is present. Message boards should also be installed to communicate with users.

*Emergency Power Supply*: This is compulsory to ensure function of vital equipment during evacuation.

*Fire Resistance of the Equipment*: Equipment shall have the ability to maintain basic functions in a fire.

# 6 Tunnel Construction Methods

In total five tunnelling methods have been identified for the crossing to Vestmannaeyjar. The 2000 report addressed three methods, namely drill-and-blast through the rock, immersed tube, and submerged floating tube, although the latter two were discounted as being impractical for the particular location. The current study has identified two further tunnelling methods, which utilise tunnel boring machine technology, both in hard rock and in soft ground, and these are addressed below.

## 6.1 Drill and Blast Method

The option of a drill and blast tunnel was extensively examined within the previous study; this section therefore provides a summary of the work done previously and expands on some of the issues relating to the Vestmannaeyjar crossing, and on the EU regulations for tunnel layouts.

### 6.1.1 Alignment and Geometry

Two possible alignments have been examined, Heimaey – Kross in Landeyjar, a distance of approximately 18.5 km with portals, and Heimaey – Eyjafjöll, which is approximately 26 km in length. The former has the significant disadvantage of requiring a major, 55m deep, 400m long cut and cover portal at Kross. The latter although longer has both of its portals within bed rock. The vertical gradient of each of the options is as high 7% in sections, and to comply with EU regulations it will necessary to reduce the maximum gradient to 5%, if this is geographically possible.

The ventilation study has shown that the 50m² cross-section proposed will be adequate, even for the long tunnel lengths involved, because of the low traffic volumes. However, from a life safety point, the flat invert of the drill and blast tunnel does not provide any potential escape facilities should an incident occur in the tunnel.

The previous study found in favour of the shorter alignment through to Kross, mainly because of the lower cost of this alignment option. At January 2000 price levels the cost of the tunnel to Kross was previously estimated at 20 -25 billion ISK. The other alignment, Heimaey – Eyjafjöll, was at the same time estimated at 25 – 35 billion ISK.

## 6.2 Soft-Ground Tunnel Boring Machine (TBM)

Tunnel Boring Machines (TBMs) are specialised machines that provide a safe method of forming tunnels through soft ground and hard rock, whilst supporting the ground being excavated. Simple TBMs comprise a basic circular shield, which is thrust forward into the ground, providing support to the roof of the tunnel, but exposing the full cut face of the ground to be excavated. More sophisticated TBMs can be designed to provide full support of the ground ahead of the tunnelling face and to prevent water from entering through the front of the machine, thus maintaining a dry and safe environment for the workforce. A TBM-excavated tunnel is circular in shape. The machines work by erecting a lining of precast concrete segments within the front shield of the TBM: the machine then jacks itself forward from the erected ring of segments: the jacks are withdrawn, and a new ring of segments erected: the cycle is then repeated. There are a number of TBM types, which provide different methods of ground support.

The selection of the TBM for the Vestmannaeyjar Crossing would depend on the depth and alignment, and hence the likely ground conditions and water pressures, selected for the crossing. Both soft ground tunnelling and a deeper hard rock alignment has been investigated for the current study. This section addresses the feasibility of the soft ground TBM alignment option.

### 6.2.1 Tunnel Alignment

A rule-of-thumb for selecting the vertical alignment for a TBM tunnel is that the crown of the tunnel should be at least one tunnel diameter below the ground, or surface of the sea bed. It should also be noted that soft ground tunnelling under water using TBMs has only previously been carried out to pressures of up to 7bar. With these considerations in mind any tunnel alignment using soft ground tunnel techniques would have to avoid the deepest part of the Áll channel between the mainland and Heimaey.

In an attempt to avoid excessive water pressures an alignment has been chosen passing to the north of the channel where the maximum depth is of the order of 70 metres. The total depth of the invert of the tunnel, even avoiding the deepest part of the Áll channel, would still extend to approximately 90 meters below sea level. These challenges although considerable are not insurmountable. The recently completed Westerschelde highway tunnel in the Netherlands was constructed through very soft ground with a mixed-shield tunnel boring machines designed to withstand pressures of 8.5bar, although the maximum pressure experienced was 7bar.

The total length of this alignment is approximately 17 km.

As the tunnel rises up to Heimaey the geology demands a gradient of 5% for over 1km and a longer section with a gradient of 2%. With such a long steep climb it may be necessary to provide a climbing lane for slow vehicles in this section. This could be achieved by modifying the cross-section of the tunnel to provide three lanes. However with the traffic level as low as it is at a level of 500 average annual daily traffic an extra lane may be an unnecessary cost, and it will probably be more practical to provide emergency parking niches approximately every 250m.

### 6.2.2 TBM Type

For tunnelling through sands under high water pressures either an earth pressure balance machine (EPBM) or a slurry machine would be required, depending on the particular geological conditions along the tunnel alignment. However Heimaey Island is made up of rock that rises out of the sea bed; any tunnel running through the sands will reach a point where there is an interface between volcanic rock and sand.

To overcome this problem a slurry shield TBM that can operate under high water pressures in sands as well as in hard rock would be required. These machines can be used in mix shield mode where an unstable working face, along with mixed geological conditions is anticipated. In this mode of operation full support is provided to the face by the extraction chamber which is filled with a bentonite slurry, in turn supported by compressed air in the pressure chamber. The air pressure is carefully monitored to prevent blow-outs or water ingress. When the tunnel face is stable, as in hard rock, the TBM can be converted into effectively working as slurry shield TBM with the face supported by the slurry in the working chamber only, with the pressure chamber at atmospheric pressure.

A slurry shield TBM is a sophisticated and expensive item of equipment and due to the type and size machine required it will have to be purpose built. The lead-time for the design and procurement of such a machine would be in excess of twelve months. This would need to be reflected within the project programme.

As stated previously, as the tunnel progresses a steel reinforced concrete segmental lining is automatically erected by the TBM to form the completed tunnel. The circular shape of the completed tunnel is not ideally suited to road traffic, but the crown can be used for ventilation fans, signage and other services, whilst the invert may be used for maintenance access and possible emergency egress.

### 6.2.3 Portal Design

The tunnel portal on the mainland would be positioned approximately 1250m from the coast. The Vestmannaeyjar Islands Road Connection Preliminary Survey Report of January 2000 identified the construction of a portal within the sands at Landeyjar as an extremely expensive operation, costing in the region of 3-5 billion ISK. However this cost is for a tunnel approach structure with a depth of 55 metres and 800 metres in length extending down to the bed rock. The portal arrangement required for a soft ground tunnel would be much shallower and shorter, thus costing considerably less.

The depth of the excavation required to launch the TBM is dictated by the required cover, generally in soft ground this is about one tunnel diameter. Assuming the cover to the tunnel crown to be 12 meters and the TBM diameter to be 11 meters, the depth of excavation will have to be around 24 meters, allowing one meter for the base slab of the structure.

Retaining systems suitable for such soft ground approach structures could include:

- Diaphragm walls
- Secant bored piles
- Caisson sinking techniques

Diaphragm walls would be constructed to allow a box, 20m wide, 25m long and 24m deep to be excavated; the TBM would then be launched from inside this box. As this excavation is likely to be below the water table a degree of ground treatment would be required to lower the local water table and ensure that the shaft is waterproof. The TBM would be launched out of the south-side of the box, and a cut and cover tunnel would run out of the north-side to the surface. The cut and cover section would run for approximately 400m at a gradient of 5%.

The portal on Heimaey would be a much simpler and cheaper affair. It would probably be in a hillside and as such require very little excavation and have no cut and cover section.

## 6.3 Rock Tunnel Boring Machine

### 6.3.1 Alignment

A TBM driven rock tunnel would follow much the same alignment as either of those proposed in the previous study for a drill and blast tunnel. The previous report found in favour of the shorter, 18.5km tunnel with the deep portal in the sands of Kross, primarily because of cost considerations. However, it may be beneficial to carry out a thorough geological study of the rock under Landeyjasandur to establish if there are points where the bed rock rises closer to the surface than is currently believed. Thus reduce the length of the driven tunnel and the size of the portal on the Eyjafjöll Mountain alignment option.

The depth of the rock TBM alignment could be in excess of 300 metres, and the resulting water pressures acting on both the TBM during construction, and on the tunnel lining during the lifetime of the permanent structure are considerable. However, greater water pressures have been experienced on hard rock TBM tunnels driven though mountain ranges, so this issue is not without precedent.

### 6.3.2 TBM Type

The type of TBM required is highly dependent on the quality of the rock. Presently little is known about the rock quality but the January 2000 report speculates that much of the tunnel lying within the tuff formations would require "considerable rock reinforcement" along with a "considerable risk of lenses in the rock with quite high transmissibility". These two comments indicate that the rock is likely to be highly fractured, and with the risk of significant water ingress a closed face TBM would be preferable.

However, it would be possible to use an open face gripper or shield TBM. Safe tunnelling would require periodic stopping of the machine, probing ahead, and possibly grouting if it was found that the rock was significantly fractured with possible heavy water ingress. This would be slow, expensive and risky and as such can be discounted.

Probably the best choice of machine would be an Earth Pressure Balance (EPB) TBM. EPB machines are currently manufactured as dual mode machines, allowing them to operated in a closed (EPB) mode but also in open mode for stable ground conditions. Such a machine could be equipped with sufficient power and disc cutters to cut through soft and hard rocks and boulders as well as soft ground above and below the water table. The spoil handling system and screw conveyor has to be modified whenever the mode of operation is changed but nowadays this can be done in less than one working shift (i.e. less than 12 hours).

### 6.3.3 Portal Design

The construction of a tunnel approach structure and portal down to the bedrock within the sands at Landeyjar would provide significant engineering challenges. The bedrock has been identified as being 50m below ground level. About a further 20m of rock would also have to be excavated to allow the launch of the TBM. This structure is considerably deeper and more expensive than the shallower structure described for the soft ground TBM option.

As the TBM would be launched from the portal located at end of the approach structure, and all materials and spoil removal would be taken through the tunnel approach, the structure itself would need to be watertight. Considerable ground treatment would be necessary, and deep sheet piles or diaphragm walls would be required to penetrate the rock in order to provide the cut-off to the ground water.

# 7 Additional Facilities and Tunnel Operation

## 7.1 Additional Facilities

A number of additional facilities and works are required to serve the tunnel. All alignment options surface on the mainland in the vicinity of Kross. Therefore a surface road of approximately 12km in length would be required to connect the tunnel with Highway 1. A shorter length of approach road is required on Heimaey. The mainland approach road would also need to be designed to prevent the risk of any flood waters from entering the tunnel. This would be done by providing a crest in the vertical alignment of the approach road, which would be above the design flood level, and continuing retaining walls from the crest through to the tunnel portal.

Other facilities will be necessary for the safe operation of the completed tunnel, and due to its remote location some of these items will contribute significantly to the cost of the project. The additional facilities required are:

- a power supply
- a water supply
- a control building and toll booths
- emergency services

Power should be supplied from both ends of the tunnel, due to the risk of the supply being cut off from one end during an incident within the tunnel. Supply from Heimaey should not be a problem as long as there is sufficient capacity within the existing undersea cables. An existing power grid network runs close to the coast at Landeyjar allowing straightforward connection to the tunnel. A fixed link between Heimaey and the mainland provides an opportunity to place electrical power cables through the tunnel, which would obviate the need for the maintenance of the undersea cables. The maintenance of both power sources is fundamental to the safe operation of the tunnel.

## 7.2 Tunnel Operation

Although not mandatory in any legislation it is probably advisable to have a control centre for the tunnel. This would facilitate fast incident response, allowing immediate closure of the tunnel and rapid attendance to any casualties. This control centre could be placed with the toll booths at either entrance to the tunnel, but preferably at the Heimaey side.

On a tunnel such as the Dartford Tunnel in the UK, located on the London Orbital Route, which includes a tolling area, the tunnel control building is manned on a constant basis, with 24-hour surveillance of the tunnel for both security and traffic management purposes. Some more recent tunnels, such as the Medway Highway Tunnel which is only 30km from Dartford, have control buildings that are generally unmanned, with microwave links feeding the information directly to the local police stations. The operating costs for these tunnels then relate to the energy consumption, cleaning repairs and routine inspection only. Therefore the ongoing running costs for such a tunnel is substantially lower due to the associated staff costs.

# 8 Environmental Issues

## 8.1 Environmental Impact

As for any major construction activities environmental assessment for the project has to be carried out according to Icelandic laws and regulations and subsequently approved by the authorities. It may be expected that spoil removal and dumping will be a large issue for this matter. Other things that may cause friction are not foreseen at the moment, as that will largely be based to the technical solution that will be selected at each time.

## 8.2 Spoil Removal and Materials Delivery

Spoil disposal and delivery of the tunnel segments and other materials to the construction sites generally has the greatest impact on the environment during the construction period. It should be appreciated that the volume of ground to be excavated from an 11 metre external diameter tunnel, extending over 18km amounts to 1.7 million cubic metres. Allowing for a bulking factor of 1.6 for rock, the actual volume of material that will need to be disposed of equates to 2.7 million cubic metres (i.e. this is a 100 x 50 $m^2$ football field with a height of 540 metres).

The location of the tunnelling worksites dictates that deliveries to site and the initial removal of the spoil from the worksites will probably have to be done by road, before being transferred onto barge. Due to the remoteness of the tunnel portal site, particularly on the mainland, this will not significantly impact on any residents in the area. There will be an impact on the residential areas adjacent to the tunnelling site on Heimaey due to the continual movement of traffic. However, the main area of concern surrounding spoil disposal is the location of an appropriate dumping site.

Ideally a tunnel of this length would be bored from both ends, and this would mean continuous working from Heimaey. The difficulties associated with transporting raw materials, including tunnel segments, to the tunnelling site, any necessary spoil removal from the island, together with the transfer of tunnelling crews to and from a site on Heimaey, especially during the winter season, should not be discounted. For this reason it is considered that any contractor would prefer to concentrate the majority of the tunnelling works as a single drive from the mainland, although it may be possible to undertake drill-and-blast tunnelling through the hard rock in Heimaey from the southern end of the tunnel. This work would require a smaller work force than that associated with a TBM drive.

For the soft ground TBM option the two forms of tunnel construction, i.e the soft ground TBM and the drill-and-blast rock tunnel, would be designed to meet at the soil/rock interface off-shore of Heimaey. Again, the great majority of the tunnelling would be carried out by TBM which would be conducted from the mainland side. This configuration would provide savings on the purchase of one TBM instead of two and in transport, but at the cost of an increased programme.

The concept of a single drive for a tunnel of this length is not without precedent. The TBMs used for the seaward drive of the Channel Tunnel formed 22km of tunnel from the site at Shakespeare Cliff to the mid-point of the English Channel, where they met French construction. One of the difficulties faced by the Channel Tunnel workforce included the fact that it took over 30 minutes to actually get to the face of the tunnel from the site when the tunnel had extended under the Channel. Further, any breakdown or maintenance of the TBM affected the programme for the entire project.

# 9 Risks and Opportunities

The risk and opportunity register is attached as Appendix C.

## 9.1 Risks

It can be seen from the risk register that the one specific area that dominates is the lack of geological/geotechnical data. Insufficient geological/geotechnical information affects the whole project life cycle from planning and design, through to operation.

Currently there are large gaps in knowledge of the geological conditions under the sea between the mainland and Vestmannaeyjar. The consequences of this on planning and design impact on possible alignments, the location of the portals and the selection of the most appropriate tunnelling method.

No matter how much site investigation is carried our prior to the commencement of construction, there will always be a degree of uncertainty regarding ground conditions. This is the case for any tunnelling project. For the Vestmannaeyjar crossing, the combination of deep undersea tunnelling under high heads of water in sands, highly complex geology with variable rock strata of unknown but potentially poor quality, and a geologically active area must be considered. Additionally, during construction, the potential of ingress of very hot water, infiltration of toxic volcanic gases trapped within the bed rock, and volcanic or seismic activity, along with the more usual risks associated with tunnelling, cannot be dismissed. Because of the depth of the sea and the prevailing weather conditions in the area which limits the marine work to fairly short windows, the logistics of undertaking a detailed site investigation are complex. Site work to obtain good quality data along the complete alignment before the commencement of construction may extend over several years. Therefore, the general conclusion of the risk workshop was that, in terms of the ground conditions that may be encountered during tunnelling, this project is extremely challenging and carries a very high risk.

It is evident that there is a large amount of uncertainty regarding the volcanic and seismic activity of the Vestmannaeyjar system. For this project to proceed this level of uncertainty would have to be reduced. What is known is that Vestmannaeyjar is geologically active, and that the level of activity is likely to increase in the future. However in geological terms the life span of this project is tiny and it is unclear how volcanic and seismic activity within the system will develop within the next 100 years. It is clear that any volcanic eruption on or near the islands could destroy the town on Heimaey, thus making any tunnel, or the tunnel itself redundant. At current levels of understanding the occurrence of such an event within the next 100 years cannot be dismissed.

## 9.2 Opportunities

A tunnel to Vestmannaeyjar would bring benefits to the local population. Communication with the mainland would be greatly improved, possibly allowing the growth of fishing and tourism on the island, as well as improving the quality of life of the island’s inhabitants. The tunnel itself could have water, high voltage and communications cables placed within it, eliminating the need for costly replacement and maintenance of undersea cables and pipelines. There may also be the opportunity to use the spoil generated during the construction of the tunnel for land reclamation or improvement.

# 10 Costs and Schedule

## 10.1 Introduction

A detailed study has been carried out to allow an estimate to be made of the costs of the tunnelled connection to Vestmannaeyjar. In order to prepare this estimate the study has reviewed the costs of recent and current tunnelling projects throughout Europe. It has also taken cognizance of the ongoing tunnelling works that are being conducted for the Kárahnjúkar hydroelectric project in Iceland, which represents the first tunnels constructed in Iceland using TBMs.

The cost figures for the 2000 study were based upon data from the Norwegian Public Roads Administration, which stated that the cost of conventional two and three-lane-wide subsea road tunnels has lain between 500 and 750 million ISK per km. However, it was considered that the quality of the rock encountered on the Norwegian tunnels would be significantly better that that anticipated for the Vestmannaeyjar crossing. Also it was recognised that many kilometres of tunnels are constructed in Norway each year, and the construction costs of these works are substantially less than anywhere else in Europe. As a direct comparison, the cost of the Hvalfjörður tunnel was approximately 800 million ISK per km. Therefore, the estimate for the Vestmannaeyjar tunnel was increased to 1000 – 1200 million ISK per km at January 2000 prices.

The methodology adopted for the production of the cost estimates reported in the current study is based on unit rates per metre of tunnelling, by whatever construction method selected. Additional lump sum items are added for particular features or items of work that will be common to all options that have been studied. This methodology is considered appropriate for a project in the very preliminary stages of study, as it is not possible to produce more detailed estimates based on actual plant, labour and materials, as these cannot be determined.

In accordance with general practice for cost estimating at such an early stage of a project, a contingency value should be added to the basic estimate, that accounts for unforeseen items and should not be regarded as uncertainty of the estimate. Following the risk and opportunity workshop, it is clear that a high contingency figure should be included for the Vestmannaeyjar crossing. The cost estimates reported below includes a contingency value which is slightly above the normal contingencies, however the estimated figures are not considered conservative, they may even be considered low, as the limited knowledge of the ground conditions presents a major challenge for both design and construction.

For clarification all costs stated below include Icelandic VAT.

## 10.2 Fire & Life Safety/ M&E Installations

Of particular importance in the construction of any transportation tunnel is the fire and life safety installations that are necessary. The earlier sections of this report present a comprehensive listing of what installations existing and future legislation will require to be included in the tunnel. It is considered that the costs of these installations were significantly underestimated in the 2000 report, and a more accurate figure has been included in the current estimates. It should be noted that, although Norway is not currently a member of the EU, they are about to embark on a major programme to improve the fire and life safety installations in all of their major road tunnels. This programme is at a significant cost.

A major component of the costs of the mechanical and electrical equipment associated with a road tunnel is located near the portal areas. These include the banks of boost lighting which provides the transition between daylight and the tunnel interior, portal sumps which trap rainwater from entering the tunnel, and the tunnel control building(s). These items would be required for a short tunnel as well as an ultra-long tunnel, which makes the costs of a short tunnel disproportionately more expensive. Beyond the transition zones the illumination of a tunnel comprises a single row of lights, and the portal sumps remain the same size irrespective of the length of the tunnel. The other M&E plant, such as emergency panels, hydrants, drainage, ventilation fans, etc., are directly proportional to the length of the tunnel.

Based upon a survey of the cost of recent highway tunnels designed by Mott MacDonald, the cost of the M&E plant equates to £2500 per metre per lane of traffic ( i.e. the M&E costs for a 2-lane highway equate to £5000 per metre). However, after a distance of 400 metres from the portal the unit cost is significantly reduced, and for the Vestmannaeyjar crossing we have assumed that the £2500 per metre would be appropriate for the entire tunnel, not for the lane of traffic. Therefore it is considered that the cost of the M&E plant for the 18.5km-long Vestmannaeyjar tunnel would be of the order of 5 billion ISK.

## 10.3 Drill-and-Blast Tunnel

The 2000 report concluded that the cost of the 18.5 km-long tunnel between Heimaey and Kross, formed using drill-and-blast techniques, would be of the order of 20-25 billion ISK at January 2000 prices. Due to inflation construction costs have risen 24% between January 2000 and March 2004, thus the cost estimate would now be 25 – 31 billion ISK. The construction of the scheme was estimated to take 6-7 years.

It is considered that the costs prepared for the previous study are an accurate reflection of the actual construction of the tunnel itself, but underestimate the value of the mechanical and electrical plant and other fire/ life safety installations that are necessary for a modern highway tunnel. It is recognised that the previous estimate did include some allowance for fire & life safety equipment, turning bays, etc, but an additional amount of 3 billion ISK should be included to ensure that the facilities and cross section are to current EU standards. Also, the value of the contingencies should be increased to reflect the risks associated with the project. Therefore, it is considered that a more appropriate cost estimate for the drill-and-blast option with a 2-lane cross section would be 38 billion ISK. This figure includes for a major excavation in the Kross area to form the portal for the tunnel: the cost of this item alone is approximately 4 billion ISK.

The schedule of 6-7 years for this option remains applicable.

A brief review of the cost estimate of the longer 26 km option through to Eyjafjöll has also been undertaken. It is considered that the total costs for the M&E equipment to achieve EU regulations would be of the order of 8 billion ISK for this option. Accepting that the previous estimate included for some M&E and fire & life safety equipment, and that only a proportion of this 8 billion ISK sum should be added to the estimate, it is considered that the overall cost of the 26km tunnel would be approximately 52 billion ISK at current prices.

## 10.4 Soft Ground TBM

A comprehensive review has been undertaken of major tunnelling projects that have recently been completed or are currently underway in Europe. These projects include highway tunnels and heavy rail projects that incorporate long lengths of large diameter tunnels driven by soft ground TBMs, such as the UK's Channel Tunnel Rail Link (CTRL). These projects show that, typically, the basic construction cost of a 10 metre internal diameter tunnel costs approximately £11,300/m or 1.4 billion ISK per km to construct. However, for projects such as the CTRL, the contract packages which include major sub-aqueous tunnelling are notably more costly than the underland tunnels. The unit rate for the Thames Tunnel on the CTRL project is significantly more than the cost of the tunnelling on the adjacent contracts. Assuming that a similar mark-up is adopted for the Vestmannaeyjar tunnel, the basic cost of the tunnelling would amount to 1,85 billion ISK per km.

The figure quoted above is only for the shell of the tunnel and does not include the road deck, turning bays and lay-bys, or any fit out with mechanical and electrical systems. The soft ground TBM option also requires a cut-and-cover portal arrangement on the mainland side, which is significantly shallower than that associated with the drill and blast or hard rock TBM options, together with the surface road to connect with the main highway, which would amount to a 2 billion ISK. Therefore the total cost of the soft ground TBM option with contingencies included is estimated at approximately 63 billion ISK.

As a comparison, the Westerschelde tunnel in The Netherlands cost €726 million for a 6.6 km long twin bore tunnel, with an external diameter of 11.340m. This equates to approximately 4.6 billion ISK per km of single bore tunnel. This cost does include all mechanical and electrical fit out, all civil works associated with connection to the existing road system, cross passages and financing. Using the Westerschelde as a guide, the total cost of the Vestmannaeyjar crossing would be would be 83 billion ISK for the completed tunnel. It is likely that the final out-turn cost of the soft ground TBM option would be somewhere in-between the two values stated.

## 10.5 Hard Rock TBM

The current work being carried out at the Kárahnjúkar Hydroelectric project has provided valuable information with regard to the costs for hard rock TBMs operating in Iceland. The bored tunnels for the Kárahnjúkar project are much smaller in diameter compared to what would be necessary for the highway tunnel to Vestmannaeyjar 7.6 metres compared to 11 metres excavated diameter. Thus the excavated face area equals 45 $m^2$ compared to 95 $m^2$. The quality of the rock at Kárahnjúkar is of significantly higher strength and integrity compared with the undersea crossing through a potentially faulted rock. Therefore it is considered that, although cognizance should be taken of the costs for the Kárahnjúkar project the cost estimates for the hard rock TBM option should be based upon international highway tunnel projects. A figure of 0.9 billion ISK per km is considered to be appropriate for an 11 meter diameter excavated tunnel, lined with segments. At this point in the design development, with such limited information available on the ground conditions, it must be assumed that the full length of the rock tunnel will be segmentally lined.

The figure quoted above is only for the shell of the tunnel and does not include the road deck, turning bays and lay-bys, or any fit out with mechanical and electrical systems. The approach facilities on the mainland side require a substantially deeper, and more expensive, cut-and-cover portal structure than that associated with the soft ground TBM, and a 4 billion ISK should be allowed for this structure and the road connection to the main highway. Including contingencies, this brings the total cost for the hard rock TBM option to approximately 43 billion ISK.

Using the unit prices identified for the hard rock TBM tunnel, the construction costs for 26km-long tunnel between Heimaey and Eyjafjöll would be of the order of 56 billion ISK at current prices.

## 10.6 Operational Costs

Information available for the ongoing running costs for existing major road tunnels is variable. Some of the more recent tunnels have control buildings that are generally unmanned, with microwave links feeding the traffic information directly to the local Police Stations. The operating costs for these tunnels then relate to energy consumption, cleaning and repairs, and routine inspections only. On a tunnel such as the Dartford Tunnel in the UK, located on the London Orbital route, which includes a tolling area, the tunnel control building is manned on a constant basis, with 24-hour surveillance of the tunnel for both security and traffic management purposes. Therefore the on-going running costs for such a tunnel is substantially higher due to the staff costs.

The annual costs for the Dartford Tunnels amounts to approximately £950,000 (120 million ISK) per year. Approximately one-third of this cost is energy consumption, and of that 75% is within the first

250 metres from each portal, where the boost lighting is located. Similarly, a major cost is the replacement of the lamps within the tunnel, and again the major part of this cost is within the first 250 metres from the portals.

The 2000 report produced for the Vestmannaeyjar crossing estimated that the annual operational cost would be of the order of 200-300 million ISK. These figures are based upon a comparison with the annual operating costs of the Hvalfjörður sub-sea tunnel, which is only 5.8 km long. The annual operating costs for that facility are 128 million ISK, and it should be noted that users of the tunnel consider that the lighting, cleaning, etc. requires improvement. So the maintenance costs should actually be increased. Based upon a comparison with the Dartford Tunnel, this cost appears high.

It is acknowledged that tolling facilities would be provided for the Vestamannaeyjar tunnel, and as such full 24-hour manning of the tolling station and control building would be likely. The running costs for the tunnel will actually be similar compared with Hvalfjörður: the amount of boost lighting at the portals being similar for both tunnels, although the central length is significantly longer. The ventilation fans for Vestmannayjar are only expected to operate intermittently because of the low volume of traffic.

Therefore it is considered that the budget figure for the annual operating cost of an 18km-long tunnel for the Vestmannaeyjar crossing would be of the order of the 200 million ISK as quoted in the 2000 report.

# 11 Further Studies and Investigations

The costs in this study should not be considered conservative, especially as the geotechnical conditions are particularly difficult. It is acknowledged that other studies are being conducted to identify the geological conditions around Vestmannaeyjar. The 2003 research programme will definitely help to improve the general knowledge of geology of the area. However, it is unlikely that the investigation methods will be sufficient to establish the geotechnical parameters that are required for the design of a tunnel, and it is considered that the results of these studies would not significantly affect either the cost or programme estimates in this report.

It is considered that should further studies be undertaken into the feasibility of a tunnel connection to Vestmannaeyjar, the priority will be to determine the quality of the rock, identify the boundaries between the different rock strata, and to enhance the knowledge and understanding of the geotechnical properties of the ground between the islands and the mainland.

# Appendix A: Tunnel Alignment Maps

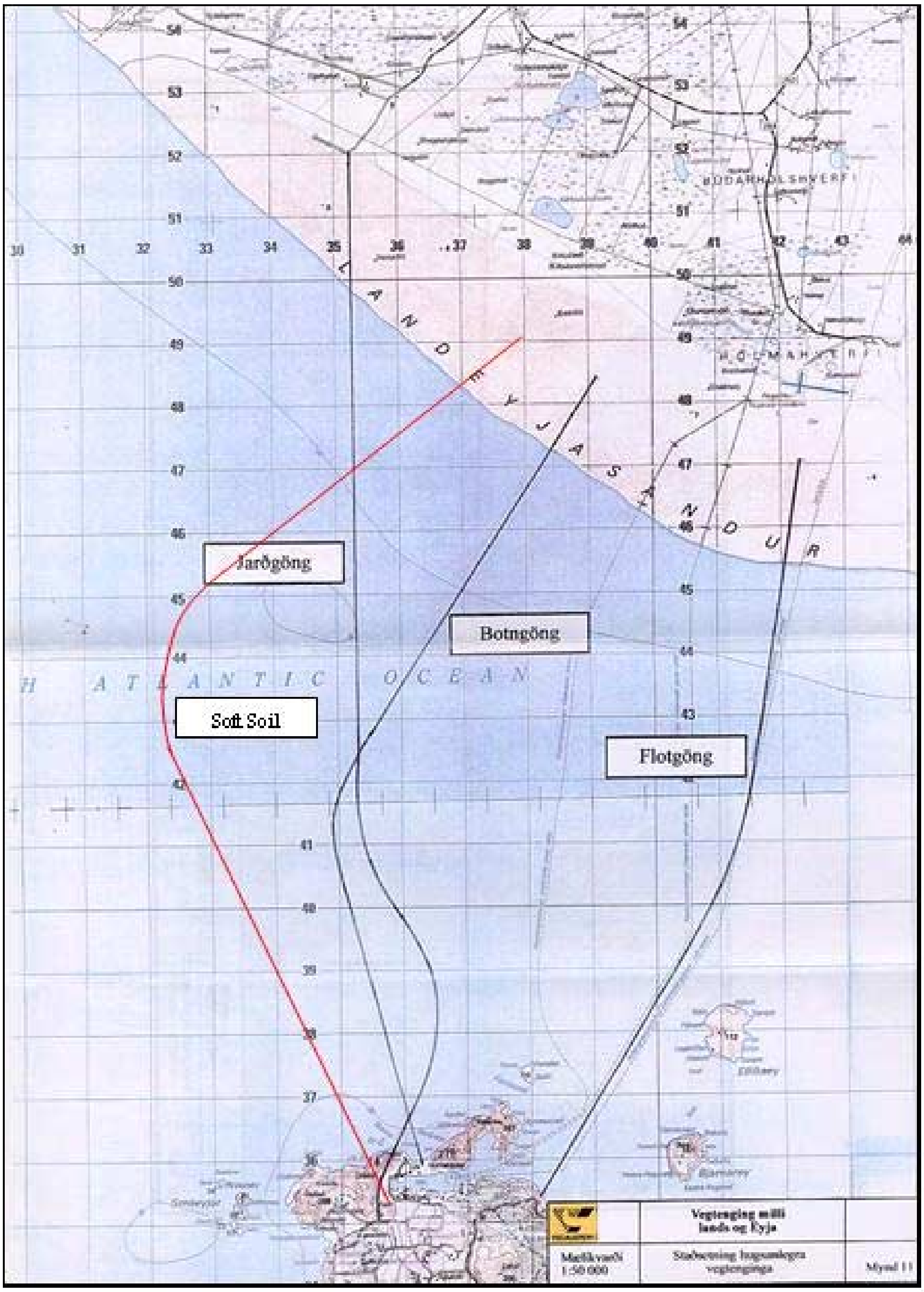



**Figure 1: Proposed Tunnel Alignments**

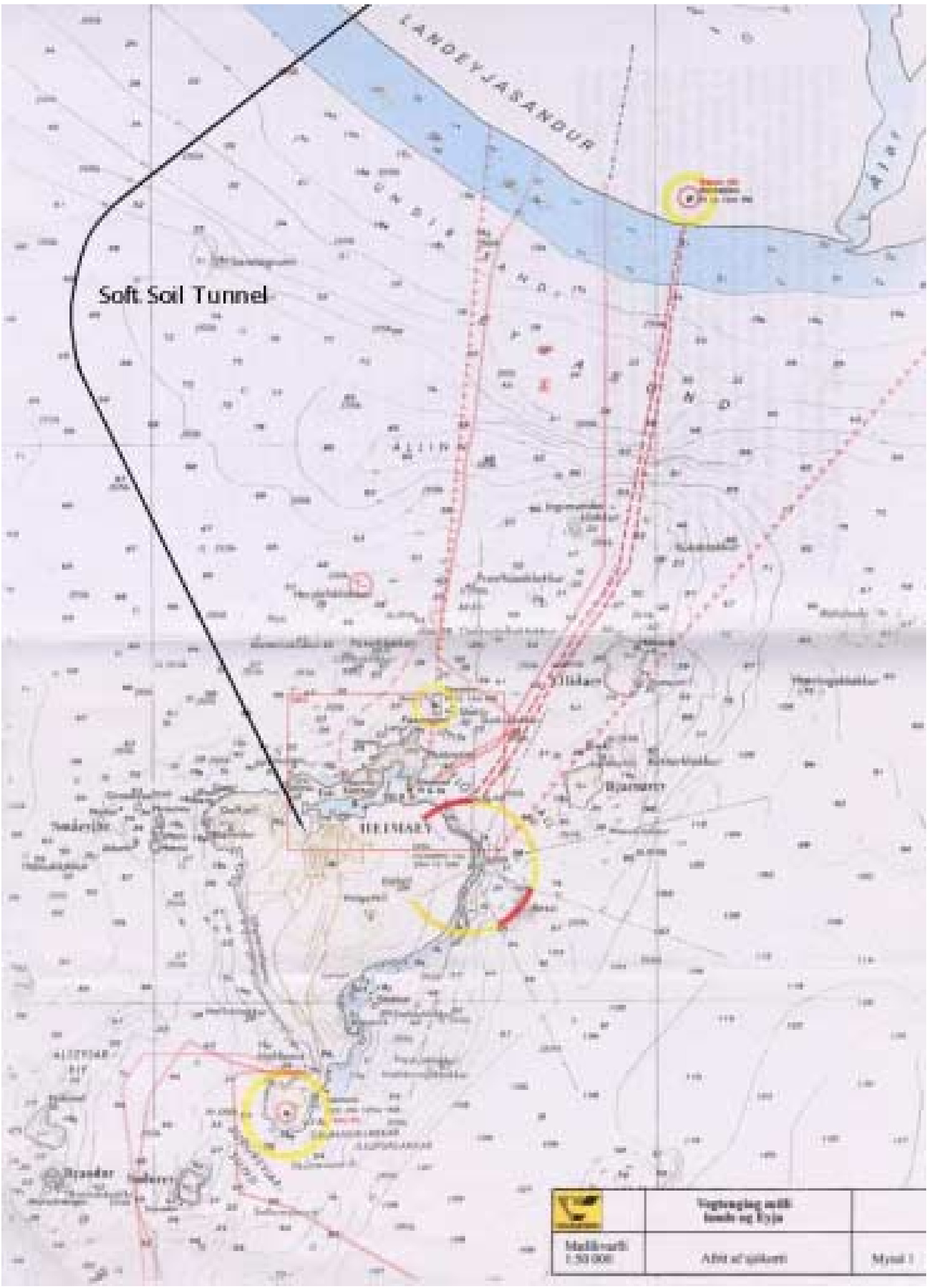
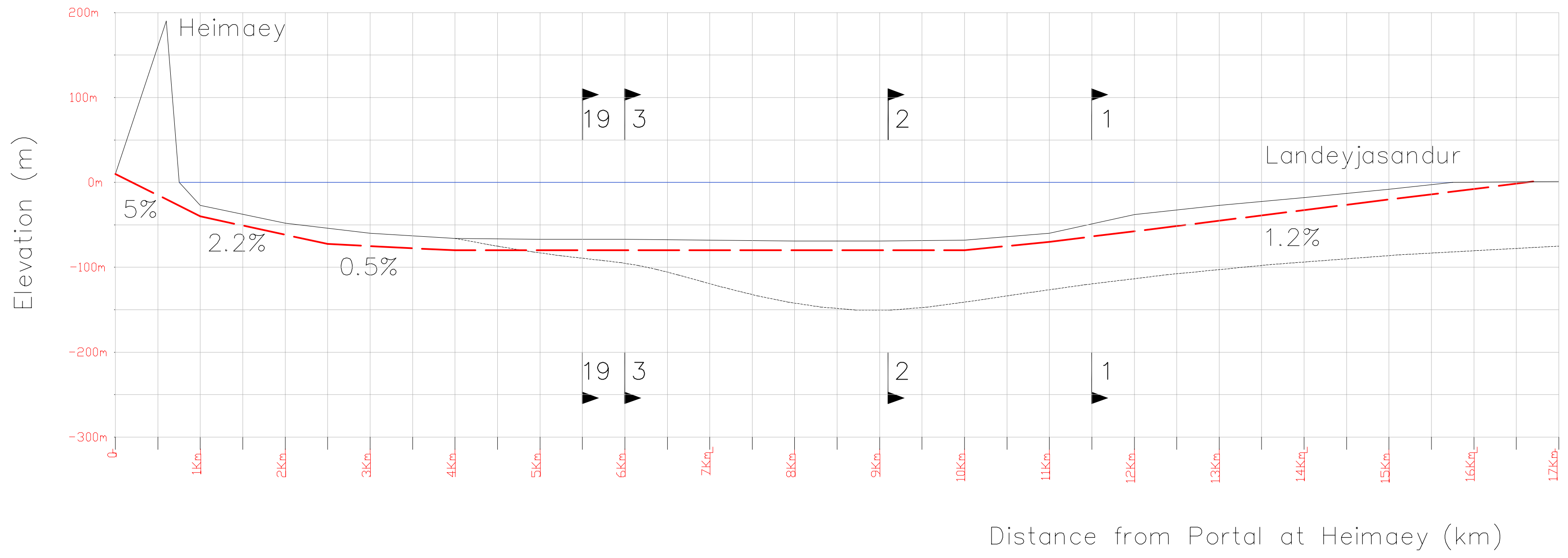



**Figure 2: Soft Ground Tunnel Alignment showing Sea Bed Contours**

# Appendix B: Drawings




Notes

Reference Drawings

Cross Sections 1,2,3 & 19 from Vestmannaeyjar Islands Road Connection Preliminary Survey Fig. 5 & 7

| Rev | Date | Drawn | Description | Ch'k'd | App'd |
|---|---|---|---|---|---|
| A | | | For Information Only | | |

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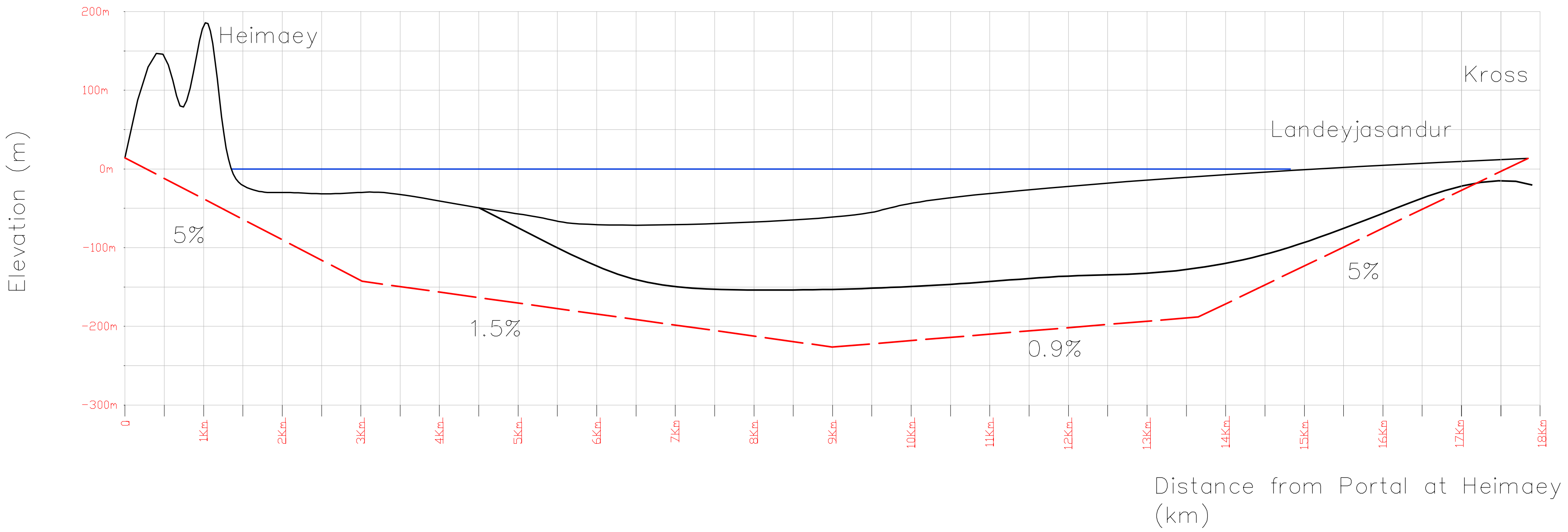
Public Roads Administration Iceland

Title
Long Section Through Proposed Soft
Soil Tunnel Alignment

| | | | | |
|---|---|---|---|---|
| Designed | MC | | Eng.Chk. | |
| Drawn | MC | | Coordination | |
| Dwg.Chk. | | | Approved | |
| Scale | 1:40000 At A1 | Project 210288 | | Status INFO |
| | | CAD file | | |
| Drawing No | | 210288/001 | | Rev A |




Notes

Reference Drawings

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|---|---|---|---|---|---|
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Client

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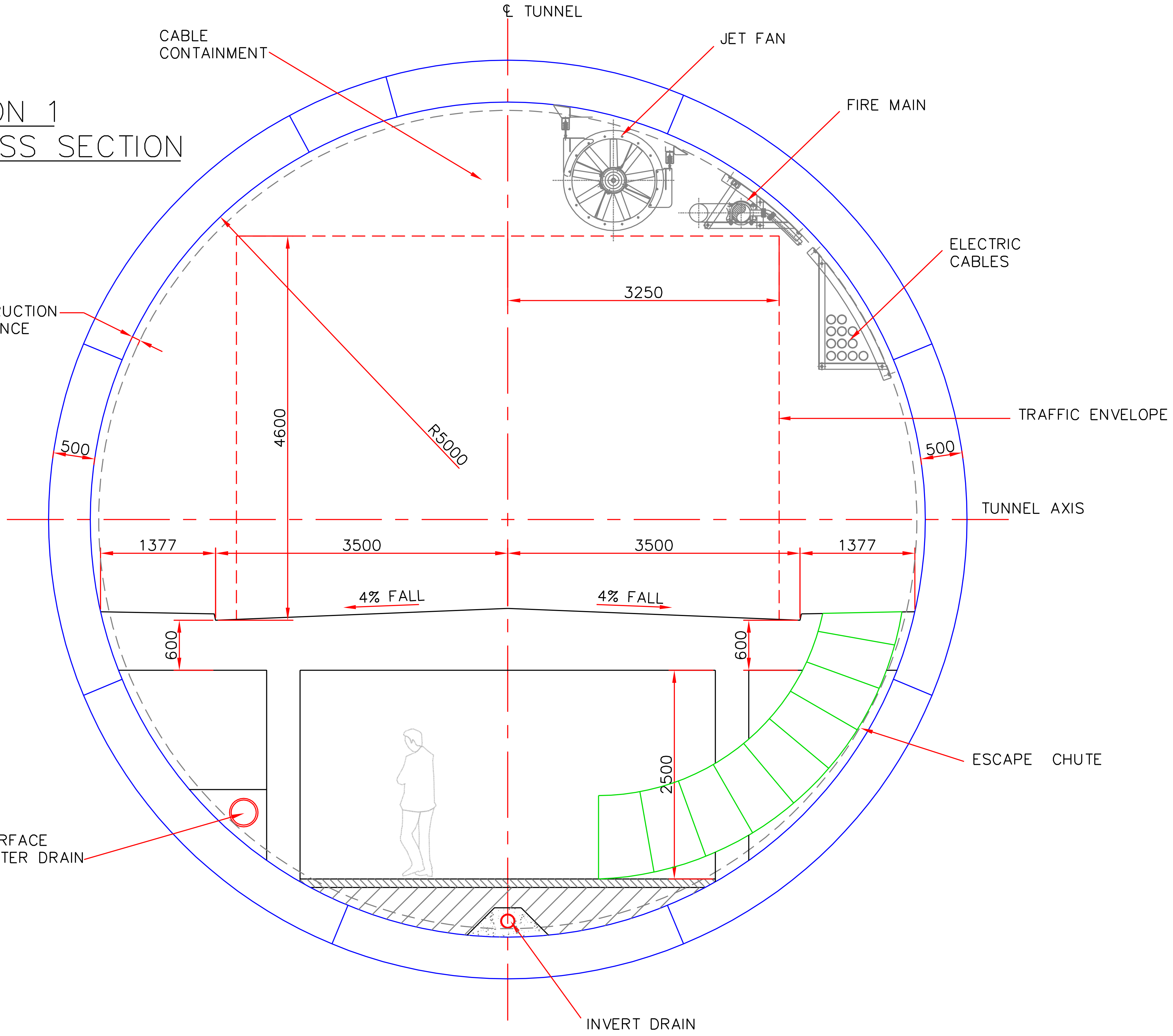
Title

Long Section Through Proposed Rock Tunnel Alignment

| | | | | |
|---|---|---|---|---|
| Designed | MC | | Eng.Chk. | |
| Drawn | MC | | Coordination | |
| Dwg.Chk. | | | Approved | |
| Scale 1:40000 At A1 | | Project 210288 | | Status INFO |
| | | CAD file | | |
| Drawing No | | 210288/002 | | Rev A |

# OPTION 1
# TYPICAL CROSS SECTION

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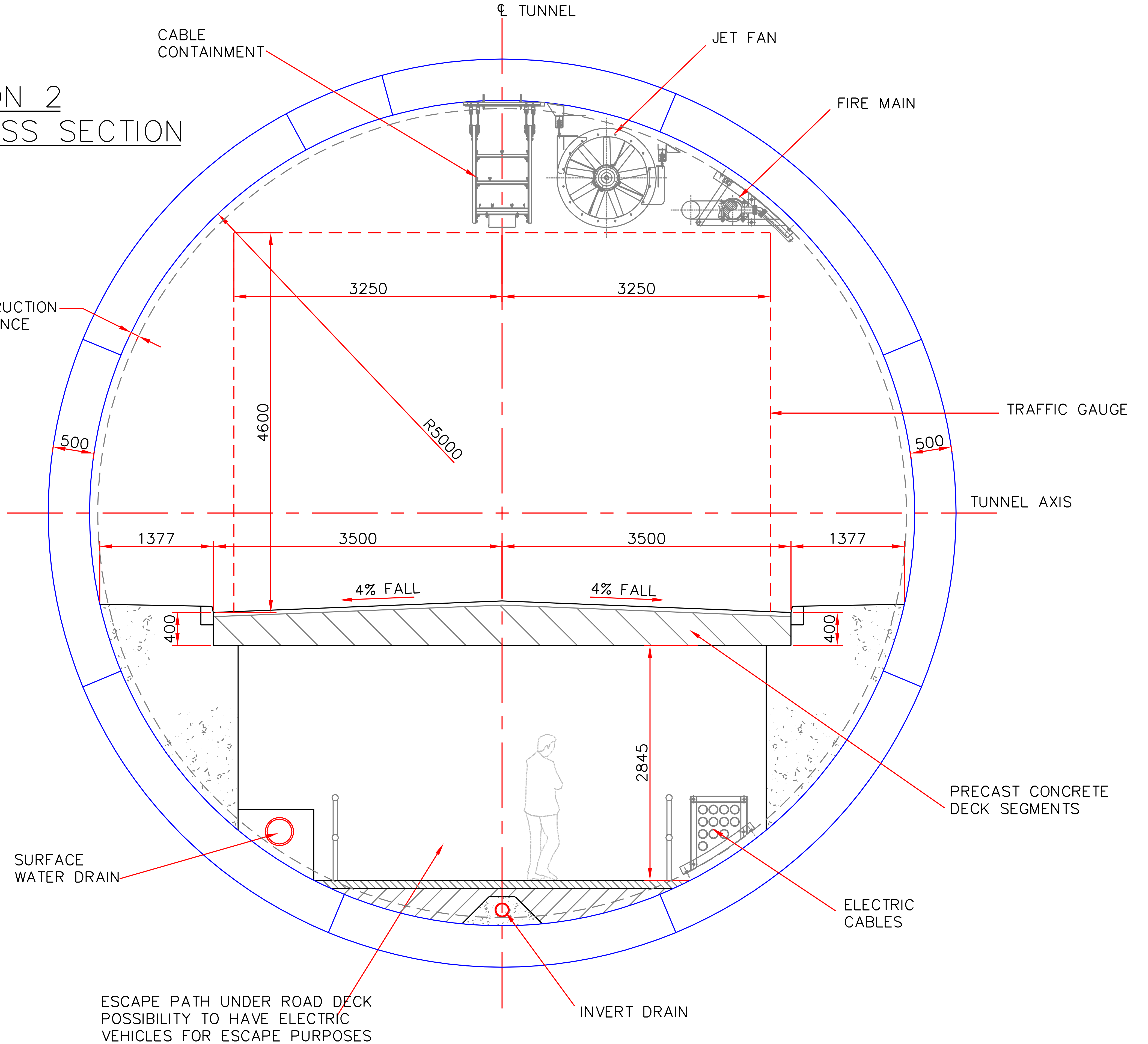
Title

Typical Cross Sections through Proposed Tunnel – Option 1 Showing Escape Chute

| | | | |
|---|---|---|---|
| Designed | MC | Eng.Chk. | |
| Drawn | MC | Coordination | |
| Dwg.Chk. | | Approved | |
| Scale | 1:25 At A1 | Project | 210288 |
| | | CAD file | |
| Status | INFO | | |
| Drawing No | 210288/003 | Rev | A |

# OPTION 2
# TYPICAL CROSS SECTION



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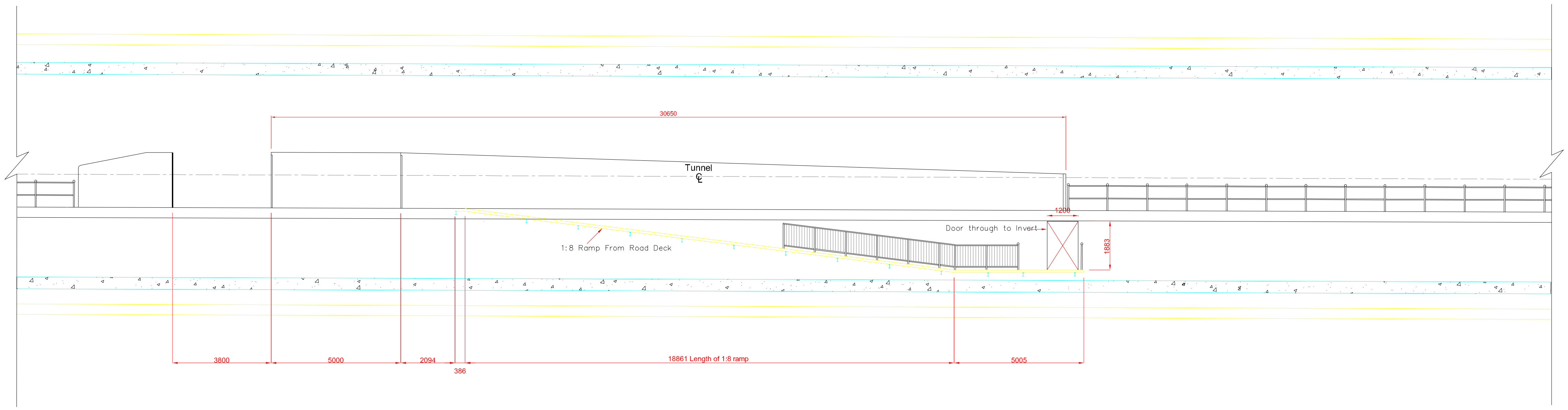
Title
Typical Cross Sections through Proposed Tunnel – Option 2

| | | | | | |
|---|---|---|---|---|---|
| Designed | MC | | Eng.Chk. | | |
| Drawn | MC | | Coordination | | |
| Dwg.Chk. | | | Approved | | |

Scale: 1:25 At A1
Project: 210288
CAD file:
Status: INFO
Drawing No: 210288/004
Rev: A




Notes

Reference Drawings

| Rev | Date | Drawn | Description | Ch'k'd | App'd |
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Title
Long Section Escape Option 2 – Ramp From Road Deck to Tunnel Invert

| | | | | | |
|---|---|---|---|---|---|
| Designed | MC | | Eng.Chk. | | |
| Drawn | MC | | Coordination | | |
| Dwg.Chk. | | | Approved | | |
| Scale | 1:100 At A1 | Project | 210288 | Status | INFO |
| | | CAD file | | | |
| Drawing No | | | 210288/005 | Rev | A |

# Appendix C: Risk and Opportunity Register

Risk Workshop held on 25 March 2003 at Línuhönnun Offices, Reykjavik.

Attendees:

Jón Haukur Steingrímsson
Línuhönnun Consulting engineers

Hreinn Haraldsson
Public Road Administration.

Kristín S. Vogfjörð
The Icelandic Meteorological Institute

Páll Imsland
Independent Geologist

Ármann Höskuldsson
Science Institute,
University of Iceland.

Gareth Mainwaring (Facilitator)
Mott MacDonald

David Powell
Mott MacDonald

Matthew Cooke
Mott MacDonald

Ewan Bennett
Mott MacDonald

| | Risk Category & Potential Risk Events | Impact | Likelihood of Occurrence | Severity | Risk Ranking | Initial Response Strategy | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Avoid | Reduce | Transfer | Retain | Analyze |
| | | | 1. Very Low | 1 | | A - Abort | S - Share | I - Insure | C - Contingency | Yes/ No |
| | | | 2. Low | 2 | | D - Design Out | C - Control | C - Allocate/ | | |
| | | | 3. Moderate | 3 | LxS | O - Other | M - Monitor | Contract | | |
| | | | 4. High | 4 | | | | | | |
| | | | 5. Very High | 5 | | | | | | |
| 1 | **Regulatory/ Approvals & Permits** | | | | | | | | | |
| | Environmental impact assessment | Delay in construction | 5 | 1 | 5 | | | | C | |
| | Compliance to EU legislation | Design changes | 3 | 1 | 3 | | | | | Yes |
| | Fire department requirements | Changes to fire safety | 3 | 1 | 3 | | | | | Yes |
| 2 | **Stakeholder Issues** | | | | | | | | | |
| 3 | **Planning and Design** | | | | | | | | | |
| | Insufficient ground information | Additional site investigations to develop stratigraphy and tectonics | 5 | 5 | 25 | | C | | C | Yes |
| | Concurrent geotechnical studies | Benefits to tunnel | 3 | 3 | 9 | | | | | |
| | Changes to EU legislation | Minor design changes may be required | 3 | 2 | 6 | | | | | Yes |
| | Lack of marine access for site investigation | Delays in site investigation | 2 | 2 | 4 | | | | C | |
| 4 | **Financial/Commercial/Contractual** | | | | | | | | | |
| | Inadequate geotechnical data | High bid costs | 5 | 5 | 25 | | C | | | Yes |
| | Inadequate geological data | Investors confidence is reduced | 5 | 5 | 25 | | C | | | Yes |
| | Form of contract | Risk sharing | 4 | 4 | 16 | D | | | | |
| | Funding terminated | Project stopped | 1 | 1 | 1 | | | | C | |
| | Inexperienced contractor | Construction delays | 4 | 4 | 16 | D | | | | |
| | Interest rates changes and inflation | Changes in project cost | 3 | 3 | 9 | | | | C | |
| | Exchange rate fluctuations | Changes in project cost | 3 | 3 | 9 | | | | C | |
| | Poor/no return on investment | No impact | 5 | 1 | 5 | | | | C | |
| 6 | **Construction** | | | | | | | | | |
| | Problems with logistics and access | Delays in construction | 4 | 4 | 16 | D | | | | |
| | Specialised/local labour unavailability | Delays in construction | 3 | 4 | 12 | | S | | | |
| | volcanic activity | Project termination | 2 | 5 | 10 | | M | | | Yes |
| | Flooding due to glacial melt from volcanic activity | Delays in construction | 1 | 5 | 5 | D | | | | |
| | Tsunami from sub-glacial volcanic activity | Delays in construction | 1 | 5 | 5 | D | | | | |
| | Ingress of very hot water | Delays in construction | 2 | 3 | 6 | | C+M | | | |
| | Water Ingress | Delays in construction | 4 | 4 | 16 | | C+M | | | |
| | Rock Mass quality | Increased cost and delays associated with extra support required | 4 | 4 | 16 | | C+M | | | |
| | Interruption in power supply | Delays in construction | 3 | 4 | 12 | D | | | | |
| | Industrial Unrest | Delays in construction through strikes | 2 | 2 | 4 | | | C | | |
| | Presence of toxic/volcanic gases | Delays in construction | 2 | 3 | 6 | | C+M | | | |
| | Incorrect TBM specification | Incorrect TBM spec may result in huge delays and increases in cost | 3 | 5 | 15 | D | | | C | |

| | Risk Category & Potential Risk Events | Impact | Likelihood of Occurrence | Severity | Risk Ranking | Initial Response Strategy: Avoid | Reduce | Transfer | Retain | Analyze |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1. Very Low | 1 | | A - Abort | S - Share | I - Insure | C - Contingency | Yes/ No |
| | | | 2. Low | 2 | | D - Design Out | C - Control | C - Allocate/ | | |
| | | | 3. Moderate | 3 | LxS | O - Other | M - Monitor | Contract | | |
| | | | 4. High | 4 | | | | | | |
| | | | 5. Very High | 5 | | | | | | |
| | **Construction continued** | | | | | | | | | |
| | Portal excavation on mainland | Construction of a deep portal in sand very close to the shore could result in large amounts of water ingress and general construction difficulties | 5 | 4 | 20 | D | | | | |
| | Construction of lay-bys and turning bays | Difficulties in construction may impact on the cost and cause delays | 5 | 4 | 20 | D | | | | |
| | Very high water pressures in soft ground tunnelling | TBM may not be able to deal with the high pressures | 5 | 4 | 20 | | | C | | |
| 7 | **Environmental** | | | | | | | | | |
| | Spoil disposal | Spoil could be used for land reclamation on Heimaey, and for flood protection on mainland | 5 | 1 | 5 | | | | | |
| | Contamination of ground water | Works could contaminate ground water | 1 | 1 | 1 | | | | C | |
| 8 | **Operations - Safety & Security** | | | | | | | | | |
| | Services within tunnel | Could place water, HV and communication cables in the tunnel | 5 | 4 | 20 | | | | | |
| | Ventilation inadequate | Ventilation could not be powerful enough to deal with traffic using the tunnel | 1 | 5 | 5 | | | | C | |
| | Smoke control | Limited to pushing smoke in one direction, drivers need to be trained to not drive into the smoke | 4 | 5 | 20 | D | | | | |
| | Maintenance of tunnel during operations | Increased risk of accidents | 3 | 4 | 12 | D | C | | | |
| | Psychological impact of driving through such a long tunnel | Increased risk of accidents due to drivers becoming tired | 4 | 4 | 16 | D | | | | |
| | Intentionally exploded device within tunnel | Could severely damage or destroy the tunnel | 1 | 5 | 5 | | | I | | |
| | Transport of hazardous goods | Increased severity of fires | 3 | 3 | 9 | D | | | | |
| | Hydrogen-fuelled vehicles | Cleaner, but pose a larger fire hazard | 4 | 4 | 16 | D | | | | Yes |
| | Ingress of hazardous gases, and failure of control of gases | Hazardous gases could enter the tunnel, resulting in tunnel closure, and possibly explosions or deaths | 2 | 5 | 10 | | C+M | | | |
| | Destructive volcanic eruption on the island | Permanent closure of the tunnel | 2 | 5 | 10 | | | | C | |
| | Volcanic eruption within the system | Temporary closure of the tunnel | 4 | 3 | 12 | | M | | C | |
| 9 | **Other** | | | | | | | | | |
| | Increase in tourism | Economic benefits for island | 4 | 3 | 12 | | | | | |