

**Considerations for a sub sea tunnel to Heimaey  
Report for the Icelandic Road Administration,  
Vegagerðin  
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**G E O T E K**



**SINTEF**

## Background and purpose

The Icelandic Road Administration (Vegagerðin) has been examining the possibility of establishing a fixed link by a proposed sub sea tunnel in rock between mainland Iceland and Vestmannaeyjar. In the Vestmannaeyjar, the island of Heimaey, where the tunnel entrance is planned, has some 4000 inhabitants and is situated some 10-12 km off the coastline near the effluent and delta of the river Markarfljót on the southern coast of Iceland.

Two specific reports have been prepared on the matter of describing a possible sub sea tunnel route to cross the sound between Mainland Iceland and the island of Heimaey. The major work on this matter was reported by Vegagerdin in 2000 (Ref. 1) and by Mott MacDonald in 2004 (Ref. 2).

A marine geophysical investigation of Vestmannaeyar and the Reykjanes ridge was undertaken by the Dr. Ármann Höskuldsson in mid 2003. This survey included seismic profiles and sidescan sonar swaths to acquire swath bathymetry and backscatter data (Ref. 3).

In late summer of 2005 the Icelandic company ÍSOR (Íslenskar Orkurannsóknir/Iceland Geosurvey) undertook a geophysical survey (Ref. 4) covering both 1) the possible landfall area of the tunnel near Kross at the mainland Iceland and 2) an alignment in the sound from Vestmannaeyjar to the mainland. The survey included 3 sections offshore and 10 refraction profiles onshore. This technical brief will base its conclusions on the latest information gained from the ÍSOR survey.

This technical brief is prepared in order to express our technical views on the possibility of constructing a sub sea road tunnel between the mainland of Iceland and the island of Heimaey based on the engineering geology experience with sub sea tunnels in Norway, Faroe Islands and the one in Iceland, Hvalfjörður tunnel. SINTEF together with Björn A. Harðarson of Geotek ehf in Reykjavik has been responsible to put the technical brief together. Furthermore, the magnitude of the probable construction cost has been assessed.

We have been involved in several of these mentioned projects including investigations, planning, design and follow-up. In addition our experience from tunnelling covers a variety of other tunnelling projects in relevant geology.

## Summary in Icelandic

### Ágrip

Að beiðni Vegagerðarinnar hafa höfundar farið yfir fyrirbyggjandi rannsóknargögn vegna hugmynda um veggöng milli lands og Eyja. Gerð er grein fyrir almennum aðstæðum til gangagerðar milli Vestmannaeyja og lands í ljósi nýjustu rannsókna sem farið hafa fram á svæðinu. Þar eru viðamestar rannsóknir ÍSOR sem fram fóru sumarið 2005 og skýrsla þar um sem kom út í nóvember 2005.

Jarðeðlisfræðilegar rannsóknir ÍSOR beindust fyrst og fremst að hugsanlegri gangaleið í bergi frá Heimaey og í beina línu til NNA að landi og komið upp á vestanverðum Landeyjarsandi. Í þessari greinargerð er sjónum beint að sömu gangaleið sem er um 18,1 km löng í bergi milli Eyja og lands, með gangamunna í Hánni á Heimaey og í landi um 1 km vestan við bæinn Kross á Landeyjarsandi. Göng af þessari lengd yrðu þriðju lengstu neðansjávargöng í heiminum og þau lengstu neðansjár fyrir almenna umferð.

Bylgjubrotsmælingar ÍSOR sýna að mesta dýpi á fastan berggrunn á leiðinni milli lands og Eyja er um 170 m og þar ofan á eru allþykk, laus sjávarsetlög nema næst Eyjum þar sem berggrunnur er ekki þakinn lausu seti. Göngin þyrftu því að fara niður á allt að 220 m dýpi og yrðu með 5-6% halla upp til endanna beggja vegna.

Út frá fyrirliggjandi gögnum má áætla að gangaleiðin frá Heimaey yrði í móbergsmyndun Vestmannaeyja á fyrstu 5-8 km. Móbergsmyndanir sem þessi eru að mestu gerðar úr túffi (gosösku), túffbreksíu (vikri og gosmalarbreksíu), bólstrabrotabergi, bólstrabergi og einstaka hraunlögum og blöndu af öllu þessu. Móbergsmyndanir eru einna óreglulegustu og breytilegustu jarðmyndanir á landinu og þar ægir saman hinum fjölmörgu ásýndum gosbergs sem myndað er við eldgos undir sjó (eða jökli). Útbreiðsla og þykkt einstakra ásýnda getur verið afar lítil og er jafnan mjög óregluleg. Ungar móbergsmyndanir af þessu tagi eru almennt ekki taldar gott jarðgangaberg m.a. þar sem breytileiki er mikill og harka bergsins er afar mismunandi. Lekt þessara jarðlaga er einnig mjög breytileg, allt frá tiltölulega þétu og vel samlimdu túffi yfir í afar opin og lek hraunlög og bólstraberg. Við borun og dæluprófanir í borholum í Heimaey hefur orðið vart við mikinn leka í þessari jarðmyndun. Jarðgöngin myndu hugsanlega fara niður úr móbergssökkli Vestmannaeyja á hluta leiðarinnar og niður í þykk sjávarsetlög sem þar eru undir. Lítið er vitað um eiginleika þessara setlaga.

Þessar jarðfræðilegu aðstæður eru afar ólíkar þeim sem eru í öllum veggöngum hér á landi þar sem mun eldri, þéttari og reglulegar hraunlagasýrpur eru ríkjandi og göng liggja oft um mjög langan veg í sömu hraunlögum.

Hljóðhraðar í berggrunni á þeim hluta gangaleiðarinnar sem er nær fastalandinu eru almennt mun hærri en á móbergssvæðinu næst Eyjum. Að öllu jöfnu þýðir þetta harðara og þéttara berg og er líklegt að þarna sé um hraunlög eða basaltinnskot að ræða að stórum hluta. Meginalli hljóðhraðamælinganna er hins vegar sá að ekkert er unnt að fullyrða um jarðlagagerð nema 40-50 m niður fyrir mældan berggrunnsflöt. Undir mældum berggrunnsfleti geta því leynst veikari jarðlög t.d. setlög eða einhverjar ásýndir móbergs. Engar sérstakar vísbendingar koma fram í bylgjubrotsmælingunum sem benda til misgengis- eða brotasvæða í framhaldi af Álnum enda benda mælingar á vegum Dr. Ármanns Höskuldssonar til þess að Állinn sé ekki brotasvæði. Upplausn mælinga ÍSOR er reyndar það takmörkuð að stök misgengi eða afmörkuð brotabelti í berggrunni koma ekki fram. Hins vegar er líklegt að einhver kvikuinnskot/eldvörp séu á þessum hluta leiðarinnar og líklegt er að Sandagrúnn sé rofið eldvarp. Gerð jarðlaga í og við slík eldvörp getur verið mjög margbreytileg og almennt ekki hagstæð til jarðgangagerðar. Segulmælingar á Landeyjarsandi benda til þess að undir sandinum geti einnig verið kvikuinnskot eða ung og rofin eldvörp.

Enginn berggrunnur fannst nálægt yfirborði á austanverðum Landeyjarsandi frekar en í fyrri mælingum. Minnsta þykkt á lausum sand- og malarlögum á austanverðum Landeyjarsandi mældist þó heldur minni en áður eða um 35-40 m skammt vestan við bæinn Kross. Þetta þýðir að gera þarf 800-1.000 m langa rennu eða göng í gegnum þetta lausa set.

Af ofangreindu er ljóst m.a. takmörkuð vitneskja liggur fyrir um jarðfræðilegar aðstæður á hugsanlegri gangaleið. Ljóst er að ef farið verður í verkhönnun á jarðgöngum milli lands og Eyja þá þurfa að koma til afskaplega umfangsmiklar og kostnaðarsamar rannsóknir sem vart myndu eiga sé hliðstæðu.

Út frá þeim takmörkuðu upplýsingum sem fyrir hendi eru má þó gera ráð fyrir að jarðfræðilegar aðstæður með tilliti til jarðgangagerðar séu erfiðar a.m.k. á stórum hluta leiðarinnar og mjög breytilegar, sérstaklega í móbergsmynduninni næst Eyjum og í og við hugsanleg

kvikuinnskot/eldvörp á gangahlutanum nær fastalandinu. Helstu áhættuþættir í gangagreftrinum eru mjög laust berg, mikið innrennsli vatns (jarðsjávar) og jafnvel jarðhiti.

Um val á hugsanlegri aðferð við gangagröft á þessu stigi málsins er ekki talið skynsamlegt að reikna með hefðbundinni aðferð við gangagröftinn þ.e. borun og sprengingum. Aðstæður eru taldar geta verið svo erfiðar, a.m.k. á hluta gangaleiðarinnar, að hefðbundin graftaraðferð myndi ekki ráða við verkið. Miklu frekar er talið, á þessu stigi málsins, að gangaborun með sérútbúinni borvél fyrir borun í góðu og lélegu bergi, sé betri aðferð og mun öruggari. Tekið skal fram að hér er ekki átt við hefðbundna gangaborvél fyrir hart berg eins og nú eru notaðar við Kárahnjúkavirkjun heldur er hér um að ræða mjög fullkomna og flókna borvél sem getur einnig borað í mjög lélegu bergi, undir miklum vatnsþrýstingi og þá eru göngin fóðruð jafnóðum með sérsníðuðum, forsteyptum einingum. Slíka vél mætti einnig nota til að gera aðkomugöngin í gegnum lausu sand- og malarlögin við munnann á fastalandinu. Hefðbundin aðferð með borun og sprengingum kemur helst til greina á gangahlutanum nær landi ef í ljós kæmi að aðstæður séu þar heppilegar.

Engin áhættugreining hefur verið gerð á hugsanlegri jarðgangagerð milli lands og Eyja. Vestmannaeyjasvæðið er, eins og öllum er kunnugt, hluti af eystra gosbeltinu sem er virkasta gosbelti landsins. Vart þarf að taka fram að a.m.k. tvö eldgos hafa orðið á svæðinu undanfarin rúm 40 ár. Hér er um að ræða sprungugos og við hvert gos opnast sprungur sem geta verið nokkrir km á lengd.

Öryggismál eru mjög vaxandi þáttur í hönnun vegganga, sérstaklega öryggiskröfur varðandi útgönguleiðir ef slyss eða óhapp ber að höndum. Erfitt er að fullyrða hverjar öryggiskröfur yrðu þegar um svo löng neðansjávargöng er að ræða en það kæmi eflaust til umræðu að mannvirkið yrði að vera tvö samsíða göng með mörgum tengigöngum á milli. Þar sem umferð um göngin yrði tiltölulega lítil gætu hliðargöngin verið e.t.v. minni en aðalgöngin og eingöngu fyrir undankomur.

Þar sem upplýsingar um jarðfræðilegar aðstæður á hugsanlegri jarðgangaleið eru af skornum skammti og óljóst hvernig hönnun mannvirkisins yrði háttað þá er, að svo stöddu, ekki talið þjóna tilgangi að gera sundurliðaða kostnaðaráætlun fyrir hugsanlega framkvæmd.

Með hliðsjón af áætluðum kostnaði við sambærileg stórverkefni sem kynnt hafa verið nýlega á ráðstefnu Alþjóða Jarðgangafélagsins má þó áætla líklega stærðargráðu kostnaðar við gangagerð milli lands og Eyja. Reynslan sýnir að jarðgangagerð í mjög erfiðu bergi er síst ódýrari við íslenskar aðstæður en erlendar. Ef reiknað er með að göngin yrðu boruð að stórum hluta með jarðgangaborvél af fullkomnustu gerð þá er heildarkostnaður talin geta orðið um 70 milljarðar króna. Ef um tvenn samsíða göng yrði að ræða, vegna öryggissjónarmiða, þá gæti kostnaðurinn orðið um 100 milljarðar króna.

## **Some major conclusions from previous reports on this project**

The report from Vegagerðin in 2000 (Ref. 1) describes a sub sea tunnel, in terms of a rock tunnel that would be formed by conventional drill & blast methods following two possible alignments to be the only feasible method for a fixed link between the mainland Iceland and the island of Heimaey. The tunnel alignments reached total length of 18km and 26km being excavated to maximum depths of 225m and 300m respectively. The shorter tunnel needs to encounter a landfall at Kross with a long and difficult ascend in loose sand and gravel, whilst the longer tunnel involves tunnelling completely in rock, or what was believed to be rock in some sense of the term. The report points out that the geological circumstances are rather unfavourable and much more difficult than for example in the Hvalfjörður where the first (and so far only) sub sea tunnel in Iceland has been constructed. The construction cost of a sub-sea tunnel was calculated to 20-35 billion ISK (2000), corresponding to approximately 27-47 billion ISK at present price level, being an adequate estimate for any of the two alternatives. The report indicated that the Westman Islands volcanic network may be looked upon as highly active and developing. There are about 70-80 recorded volcanoes in the Vestmanna area, and at least 22 eruptions have taken place during the last 10.000 years. The area is seismically active and at least three volcanic eruptions have taken place during the last 110 years (Ref. 1). Further it reported that the sub-aqueous channel Állin in the strait between the islands and the mainland may be a source zone for earthquakes and movements along fractures.

Based on seismic investigations the report from the Dr. Ármann Höskuldsson (Ref. 3) does, however suggest that Állin is not an active tectonic feature.

Mott MacDonald prepared an independent review (Ref. 2) of a tunnel connection to Vestmannaeyjar in 2004. The report from Mott MacDonald included also an evaluation of a tunnel method consisting of a circular tunnel formed by TBM excavation that could be performed at a shallower depth in the soft ground by a dedicated type of machine. The Mott MacDonald report also includes an option for a hard rock TBM. Their report concluded updated cost estimates to 2004 levels, which were comparatively higher than predicted by Vegagerðin in 2000 (with inflation adjustment included) and reached; 38 billion ISK for drill & blast tunnel; 63 billion ISK for soft ground TBM; and finally 56 billion ISK for a hard rock TBM. The TBM method will produce a significantly larger tunnel cross section than would be by the drill & blast method and subsequently Mott MacDonald proposed the excessive space to be utilised as emergency exit. The report also concludes that the tunnelling conditions will be very demanding and cannot be directly compared with previous or ongoing tunnelling projects in Iceland.

## **General requirements**

The most important requirement for a tunnel of this kind is that it is possible to find and decide upon a tunnel route with sufficient rock cover and adequate rock quality. The decision process should adhere to well accepted standards utilised in similar projects, comprising a stepwise build-up, through thorough pre-investigations, of the basis for feasibility and financial considerations. These aspects will be dealt with in subsequent chapters.

We assume that a future tunnel project will comply with Norwegian tunnel design standards, as these have been used as guidelines for other tunnels of the Icelandic public road network. A tunnel to Vestmannaeyjar will necessarily be a low-traffic tunnel, with a traffic density most probably less than 1000 vehicles per day as an annual daily average. According to the regulations of the current version of Handbook 021 two lane, single tube is thus relevant. However, the necessary length, probably becoming in the range of 20km (approximately 18km rock tunnel and

1km concrete portal structure), will impose a design class where a high standard of safety arrangements is required. At present we have no references on the emergency and safety requirements for such long road tunnels, neither sub sea nor for land tunnels. It is expected, however that relevant standards in the future may be stricter than current standards. For that reason, no less than the standard of the Hvalfjörður tunnel must be foreseen, and maybe with even certain additional elements such as rescue stations and surveillance cameras (CCTV). Maximum inclination of 6% according to Handbook 021 will be a question of convenience vs. total length, but that will probably not make a large impact on the foreseen length. The EU regulations are currently specifying a maximum gradient of 5%.

A certain challenge associated with the geometry, is that on the mainland side, it is a lack of rock outcrops above sea level in the vicinity of an expected tunnel route. Information at hand indicates a depth of sand and gravel of around 40m, which means that the tunnel floor will be at around 55m depth. Consequently the tunnel will have to either be considerably longer to find shallow bedrock, or, a challenging downhill slope section will have to be constructed inside a complete diaphragm wall box in the sand and gravel deposit suspected to cover the rock topside in the delta area. A vortex shaped road (like a corkscrew) inside a 60m diameter barrel shaped wall of softpiles is another plausible solution, leaving room for a central construction pit suitable for lowering of heavy and large goods (TBM sections, lining, drill jumbos, shotcrete equipment etc.).

The tunnel would become the 3<sup>rd</sup> longest traffic tunnel under sea in the world, next only to the Channel tunnel between England and France (50 km) and the Seikan tunnel in Japan (54 km), both twin tube rail way tunnels. The fixed link across the Great Belt in Denmark consists of two parallel sub sea tunnels, each appr. 8km long. The longest sub sea road tunnel in the world in use to day is the Bømlafjord tunnel in Norway, approximately 8km long. The crossing to Vestmannaeyjar will thus be the longest sub sea tunnel open for the general public. In that perspective, it should be emphasised that a tunnel crossing of such a long stretch of open sea is likely to face a requirement to have twin tubes as there is no other credible or reliable means of a safe emergency exit. The emergency aspects are discussed in further details in a later section of the report.

A minor point to consider taking into account with respect to drive in long tunnels is that 2-5% of the public is actually suffering from fear or aversion against driving in tunnels.

### **Geological considerations based on the ÍSOR report of 2005**

It will not be a surprise to anyone, though, that the major considerations will have to be whether or not a tunnel in the actual geology is a feasible endeavour, in soil materials or rock. We have studied reports from various sources, see reference list, the main references being the report from the Dr. Ármann Höskuldsson and lately the report from ÍSOR which describes the findings from a refraction seismic survey conducted in 2005. As far as to our knowledge there are no other dedicated geological studies or mapping available other than those listed amongst the references, nor is it expected that such investigations exist at this stage for the marine and sediment covered area, which in fact will constitute almost the total length of any practical alternative. The report from ÍSOR (Ref. 4) includes also a single example of an interpreted seismic profile of somewhat 14 km length, made from a surface towed refraction recording set-up, see Figure 1 below.

In Figure 1 below an interpretation of the results from ÍSOR is presented with a typical tunnel alignment indicated to show the depth of the tunnel compared to the interpretation of geological formations. The assumed tunnel alignment is shown with dotted line, given the tunnel being constructed as a rock tunnel. Demarcation between various areas of changing P-wave velocities

are shown as dotted lines with question marks to indicate the uncertainty of the interpretation. The survey itself does not provide sufficient proofs to say that the model as shown above is the absolutely right one.

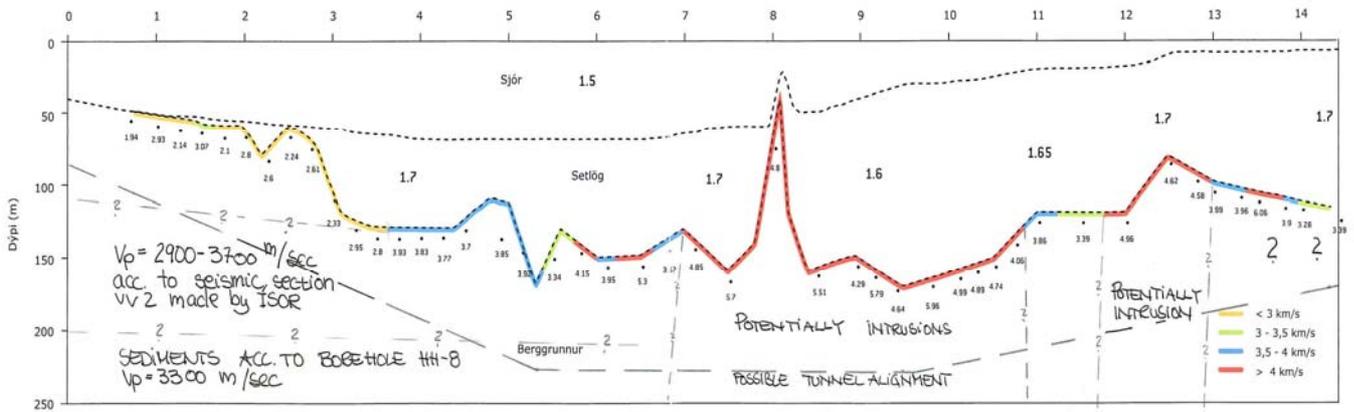


Figure 1. Longitudinal section with interpreted geology (numbers on top indicate km)

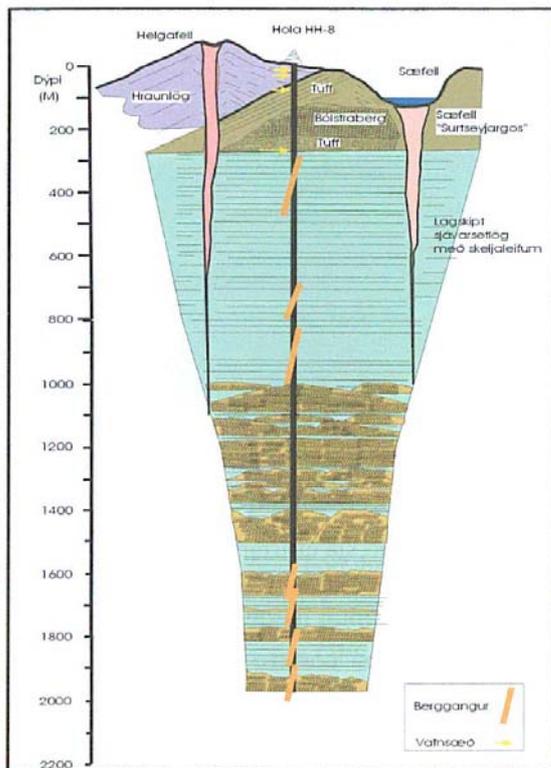


Figure 2. Stratigraphy along bore hole HH-8 at Heimaey, from ÍSOR report

Translation of some terms in Figure 2

- Bólstraberg* = Pillow lava, could contain tuff and ash.
- Sæfell "Surtseyjargos"* = Socalled Sæfell formation (similar to the Surtsey eruption in 1964).
- Lagskipt sjávarsetlög með skeljaleifum* = Marine sediments with shell fragments.
- Dýpi* = Depth below top of bore hole, sea datum is at appr. -100m at the depth scale in figure 2.
- Berggangur* = basalt dykes.
- Vatnsæð* = Water inflow.

For the construction of the longitudinal section in Figure 1 we have also applied information from the ÍSOR report (Ref. 4) that provides data on the stratigraphy as interpreted along bore hole HH-1 at Heimaey (see Figure 2).

According to the results from the ÍSOR report the depth to the bedrock is indicated at around -170m at the maximum. With a design requirement of minimum of 50m rock cover the tunnel alignment will be located at approximately -220m. The assumed dimensioning sections of the

tunnel alignment with respect to the vertical depth will then be the low points at approximately 5,5km and 9,5km.

Bedrock P-wave velocities are also indicated, being representative only for shallow rock depth as the penetration is limited. According to ÍSOR a general depth of 40-50m can be considered relevant for the P-wave velocities indicated along the profile. The profile shows a wide lateral scatter of P-wave velocities for the anticipated “bedrock”, varying from less than 2.000m/s to almost 6.000m/s.

Even if this method tends to over-estimate the P-wave velocities, the profile does indicate substantial sections of “bedrock” with such low P-wave velocities as indicating extremely loose rock or cemented sediments (between 1.900 and 3.000m/s in the shallower, left hand section). However, due to the descending tunnel profile towards the low point, a possible tunnel may encounter these particular geological conditions during a section with a length of a few km from the portal at Heimaey. P-wave velocities are normally used to identify geological formations and assess their influence on excavation work for sub sea tunnel projects.

#### From Háin at Heimaey to refraction profile VV2 (1,4 km)

*Source of information; geological mapping of Vestmannaeyjar, borehole data on Heimaey, tidal measurements on Heimaey.*

The tunnel would start in the moberg formation on Heimaey at Háin (socalled Nordurkletta-formation) and most probably prevail in some sort of moberg formation for the whole 1,4km section. The Nordurkletta formation (as all moberg formations) are formed during volcanic eruptions under sea (or ice). The main characteristics of such formations is the variety and irregularities of different facies (units) of the volcanic material depending on the conditions during the eruption. The Surtsey eruption (1963-1967) is a typical example of such an event and, perhaps to a lesser extent, the Heimaey Eldfell eruption (1973). The presently visible part of the Nordurkletta formation (such as Háin, Dalbjall and Stóra Klif) is made mostly of palagonite tuff (volcanic ash, cemented to a variable degree) but other common units of a typical moberg formation are tuff breccia (tuff with basalt fragments), ash, pumice, scoria, pillow breccia (basaltic fragments in tuff groundmass), pillow lavas (glassy pillows of lava with glassy basalt fragments around) and basaltic lavas, all depending on the availability of water (and pressure) around the eruptive vent and the type of eruptive phase. All the pyroclastic units of the moberg formations are usually very irregular and variable in volume and extent and subvertical and inclined contacts between units are common. The characteristics of these units can change very rapidly from one place to another making the moberg formations the most inhomogeneous rock formation in Iceland. The degree of palagonite cementation (consolidation) is also highly variable, ranging from loose, glassy ash and pumice, to intermediate cementation of pyroclastic breccias and pillow lavas to well cemented tuffs and lava flows. The permeability of these formations is therefore also variable, ranging from very high permeability (K up to 1m/s) in unaltered, porous lavas, pumice, scoria and pillow breccias and pillow lavas to much less permeable, highly palagonized tuffs ( $K = 10^{-3} - 10^{-6}$  m/s).

Evidence from existing boreholes in the Nordurkletta formation indicate very variable conditions. Borehole HB-1, located only approx. 500m from the assumed tunnel portal, 10m above sea level, shows a mixture of highly permeable lava flows and pillow lavas and some glassy sands and tuffs in the top 190m. Thick units of unconsolidated pumice could also be present. The top 190m of the hole was lined and repeated concreting was necessary in the top 80m due to large inflows of (sea)water and presumably also, due to loose and unstable formations. Below 190m the rock formations change into stratified marine sediments with shell fragments which extend many

hundreds of meters down, see Figure 2. Measurements of P-wave velocities in the borehole indicate a velocity of 3.300m/s for the marine sediments and som 3.000m/s in the overlying moberg formation. The thickness of this sedimentary strata was confirmed in the deep borehole HH-8, located some 2km south of the assumed tunnel entrance. The hole is drilled through relatively dense moberg tuff and pillow lava formation from sea level down to 180mbsl where it enters the marine sediments which extend down to 900mbsl.

Evidence from borehole FH-04 drilled 120m into Heimaklettur moberg (approx. 1km from the assumed portal location, top of hole few meters above sea level) indicates a rather large horizontal aquifer below 86m depth. The bottom 5m of the hole were drilled in loose sand (or pumice).

The geological and hydrogeological conditions in moberg formations are in general variable and of quite different nature than in the much older and more regular lava pile stratigraphy on the mainland where all existing road tunnels in Iceland are located. (Some limited sections of older hydropower have been excavated in much older rock than “regular lava pile”.)

The tunnel alignment would most probably be within the Nordurkletta moberg formation, or similar, at least towards the location of refraction profile VV2 north of Heimaey.

#### 0 – 3,5 km on refraction profile VV1.

*Source of information; refraction profile VV2, southern part of refraction profile VV1.*

At the location of refraction profile VV2 (approx. 1,4 km from the assumed portal location and at the origin of profile VV1) there seems to be a 50-100m thick strata on the sea floor with low velocities of 2.400-2.600m/s at the location of the tunnel line, occassionally as low as 1.900m/s. This is interpreted as loose moberg units of unknown character. Underneath, another velocity refractor at depth of 80-150mbsl is evident with velocities of 2.900-3.700m/s. This is most likely also a moberg formation, possibly with some permeable lava flows or well cemented sediments.

The refraction signals on profile VV1 begins some 0,5km further to the north and shows a sea floor strata at the depth of 50-70mbsl with velocities between 2.000-3.000m/s. The thickness is not known. This velocity correlates in general with permeable moberg formation, moraine/tillite or consolidated sediments, where the moberg is the most likely interpretation. The lowest velocities recorded by refraction seismics in the Hvalfjorður using bottom cable were very limited zones of 2.300m/s to 2.500m/s. Refractions seismic surveys in the Faroe Islands did not yield any similar low velocity.

Similar conditions prevail to the 3,0km distance along profile VV1 where the rock surface horizon plunges down to a depth of 130mbsl overlain by very loose marine sediments, 60-80m in thickness and with velocity of 1.700m/s. At the distance mark of approx. 3,5km a sudden increase of velocities occur to 3.700-3.900m/s in the basement rock. The plunge in the basement rock horizon and the sudden increase of velocities could possibly reflect the outer boundary of the Vestmannaeyjar moberg formation.

The ground conditions in this partiucular section must be considered as adverse ground conditions for rock tunnelling being associated with high uncertainty and most risky.

Whereas the penetration of the refraction seismic is only 40-50m nothing can be concluded about the rock character at greater depths. The thick marine sediments below the Vestmannaeyjar moberg could possibly be in this area at approx. 180-200m and below.

### 3,5 – 6,5 km on refraction profile VV1

*Source of information; refraction profile VV1 and VV2 and report by Dr. Ármann Höskuldsson.*

The refraction seismic velocities at the rock head indicate a basement horizon below the loose, marine sediments with velocity of 3.800-4.000m/s at the 3,5km mark whilst increasing to around 4.000 at the 6.5km mark on profile VV1. The surface is rather irregular at the depth of 100 to 160 m. This is interpreted as permeable lava flows but well cemented moberg could also correlate with this velocity.

Taking into account the results from a perpendicular seismic survey line, the VV1, a flat horizon can be established that cover the depth from -100m to -200m. The survey indicates that the P-wave velocity in this horizon varies from 2.900-3.700m/s.

A topographic depression occurs at approximately 5,5km that could possibly be the rim of the Állin. According to (Ref. 3) Állin terms not to be the result of faulting as the survey did not find indications of faulting mechanisms in the western part of Állin.

At greater depth there is no information from the survey on the stratigraphy, such as below 180mbsl.

### 6,5 – 10,5 km on refraction profile VV1

*Source of information; refraction profile VV1.*

Between distances 6,5 to 10,5km the velocity in the basement horizon is increased and is mostly 4.800-5.500m/s. This is interpreted as being dense basaltic lavas or volcanic intrusions. The marked peak around 8km on profile VV1 (Sandagrúnn) is most probably a volcanic intrusion making Sandagrúnn one of 50-60 sub sea volcanos in the Vestmannaeyjar area (Ref. 1). The geology can be very complex in and around such volcanoes, which may be reflected in the varying velocities next to the main intrusion. At the 9,5km mark the basement horizon reaches maximum depth of 170m with overlying loose sediments of 140m in thickness.

### 10,5 – 14,3 km on refraction profile VV1

*Source of information; refraction profiles VV1 and VV3.*

From the 10,5km distance marker on profile VV1 towards the mainland the velocity of the basement horizon is variable from 3.300 to 6.000m/s. Similar or even higher velocities are measured in profile VV3 intersecting VV1 at the 12,5km marker. Velocities between 4.000 and 7.000m/s are common in this location on profile VV3. The high velocities indicate dense basaltic lavas but intrusions should not be excluded, especially such as associated with the peak in the horizon at the 12,5km marker. The ground conditions may laterally change frequently during the course of tunnelling in this section as the P-wave velocities are changing rapidly. The basement horizon slopes gently down towards the mainland at the north end of profile VV1, reaching 110m at the 14,3km marker with approx. 100m thick, loose sediments above.

### End of refraction profile VV1 to landfall west of Kross (2,4 km)

*Source of information; onshore refraction profiles, aeromagnetic survey*

The presence of loose, thick sedimentary deposits of mostly sand and gravel in the Landeyjarsandur area is well known. The thickness is up to 250m in the eastern part, but thicknesses of 50-80m is common in the area around Kross. Results from the refraction seismic survey indicate some rock mounds below the sediments with the shallowest depth to bedrock of about 35-40m west of the farm Kross. The velocities in the mentioned bedrock mounds in this area are relatively high (mostly 4.500-5.500m/s) and they also show strong magnetic anomalies. This indicates the presence of volcanic intrusions in the bedrock. Velocities between the magnetic anomalies (3.300-4.000m/s) indicate moberg, consolidated sediments and/or permeable lavas.

### Remarks to the ÍSOR survey

It is difficult to establish a geological model with high confidence based on the information from the current ground investigations, but some important elements have however been determined resulting from this geophysical survey. The following considerations can be made as far as the results from the performed survey are concerned:

- The velocities found are valuable and useful for the current stage of the project in verifying the presence of weak moberg formation rocks in the area mixed with layers of sediment horizons.
- Some major low points in the bedrock head at appr. 5,5km, 7,5km and 9,5km may represent major zones of weakness. Beneath a smooth seafloor these low points in the bedrock represents canals with vertical drop of several tens of meters, however the scale is rather compressed and therefore it is not possible at this stage to conclude on the origin and content of these low points. The low point at appr. 5,5km could be the possible northern rim of the Állin.
- The experience from the Hvalfjörður tunnel and two sub sea tunnels in the Faroe Islands is that using refraction seismic survey is very difficult for the purpose of identifying weak zones in the basaltic bedrock, composed by horizontal layers. Weak layers in between more solid and high velocity layers are not shown, further velocity anomalies may not necessarily represent sub-vertical and vertical weak zones.
- Combining the ÍSOR results with the information from the HH-8 drilling a horizon of sediments can be expected at a depth of 200m below sea level close to Heimaey.
- Another horizon of mixed sediments and loose rock can be expected at approx. 100 to 200m below sea level at the Heimaey side, being the layer above the thick sediments.
- Towards the mainland of Iceland intrusions may appear frequently, but irregularly. The information does not cover any significant depth in the bedrock, or below the top head of the rock as the penetration by this method is rather limited. This is of course a draw back of the method as it does not provide any indications on increased velocities towards depth indicating an improved rock mass quality.
- The longitudinal section does not indicate any weakness zones in terms of vertical or sub-vertical velocity anomalies, however, the report indicates vaguely that irregularities in seismic basement velocities may be due to local geological anomalies (intrusions and fractures) but the resolution of the method does not allow any small scale interpretations.

### General remarks on geological

The two most significant geological features revealed so far, are: 1) The area in question is directly inside the southern part of the active Eastern Volcanic Zone in Iceland. 2) At a certain depth, relevant for possible tunnel alignment, there are thick layers of marine deposits. Even if a

tunnel alignment, or a major part of it, could be found within the volcanic rock formations (above the sediments), certain adverse features must be considered:

The area is the most active volcanic part of Iceland and a part of the continental divide in Iceland with the latest eruption having taken place only 30 years ago. The rock of such extremely young strata is known to be of a complex nature, largely characterized by weak, brittle, jointed and porous rocks accumulated in frequent and varying streams, flows, dykes and sediments. Lava flows may be in shape of pillow lavas and moberg. Intense erosion and movements in the young strata will have contributed to the complexity in the deposited and remaining rocks, see Figure 3 below. In addition to that, high thermal gradients and aggressive, hot ground water is to be expected.

The active fissures in the Vestmannaeyjar area are generally striking N40°E. Pending on the actual locations of the landfalls of the tunnel on both sides the tunnel would be aligned with an angle to these fissures thus resulting in an unfavourable parallelism rather than a perpendicular intersection. The eruptions in the area, such as the Surtsey and Heimaey eruptions were not one-spot eruptions, these were eruptions along active fissures with length in the range of 3-5km.



Figure 3. Dalfjall (Photo courtesy of Haukur Jóhannesson)

Figure 3 above shows the moberg formation on the western tip of Heimaey.

Whilst coring and drilling in the moberg-formations frequent and significant core loss has often been experienced, especially in semi consolidated tuffs and breccias and porous pillow lavas.

An additional feature, making such rock mass conditions unfavourable for tunnelling and especially for controlling potential water leakage, is the probable lack of confinement stress due to

the ongoing dividing tectonic action between thin lithosphere plates. Confinement stress is important in tunnelling for the stand-up ability of jointed rock and for effective use of grouting pressure.

A different but nevertheless relevant geology can be studied in an uncovered state at the coastline near Grindavík, where the western “divide branch” enters the south coast. On this location frequently changing lava flows and interbedded sediments can be observed.

Interpretation of pre-investigations, which usually can rely on systematic and/or enduring geological strata and joint systems, will be much more uncertain in such geology. And it is a kind of rock mass that will challenge a normal, foreseeable tunnelling method.

An image from the area close to Grindavik, see Figure 4 below do perhaps illustrate the actual variety and easily eroded, loose rock interbedded with glass hard, jointed basalt.



Figure 4. Image from Grindavik (photo courtesy of Anders Beitnes)

## The need of detailed geological pre-investigations

It would be a real challenge to design, perform and not least to finance a future detailed pre-investigation program, which could adequately reveal the actual geological conditions and provide a robust base for the determination of a best feasible tunnel route as well as a reasonable certainty in the investment cost estimate. Due to the length of a potential tunnel crossing and the changing conditions, both laterally along the route and vertically with the layered stratigraphy, the geological pre-investigations need to be very comprehensive.

Due to the lateral and vertical changing conditions, even such a comprehensive programme may not provide an accurate image of the real geological formations that will be encountered whilst tunnelling, thus the tunnelling project remains with a significant risk and uncertainty.

In the following some aspects of investigations are listed:

- Refraction seismic profiling is normally a very useful investigation method for sub sea tunnels, but has proven not to be very suitable in this kind of layered rock because embedded weak layers become “invisible”. Bottom cable seismic is expensive and subject to malfunctions in rough sea. Towed cable set-up is more efficient, but it will normally have poorer penetrability as has been shown by the survey done by ÍSOR.
- Reflection seismic profiling, preferably in a 3D streamer set-up, may have advantages. But, if the stratum is complex, even the densest pattern of reflection seismic will become equally difficult to interpret.
- Vertical or inclined core holes. Core drilling from floating vessels may be needed in an unprecedented amount and still that will just provide examples of rock type distribution. Drill ships of the actual kind are very expensive to operate, see figure 5.
- Directional drilling of core holes from land and designed to follow a suggested tunnel alignment, is a method with better coverage. However, this method does not hold a proven track record for holes exceeding the length of 6-700m, and holes of such a length that could be of significance here are still to be developed.
- Thorough risk analysis to identify and evaluate the various risk elements associated with a possible tunnelling project involving a sub sea crossing to Vestmannaeyjar. Particularly focusing the probability of an eruption along the active volcanic fissures in the area and the consequences if such an event takes place during construction or operation of the tunnel.



Figure 5 Investigation vessel

Irrespective of what indicative pre-investigations may tell, the above indicated kind of geology with significant local and random variations has to be considered.

As has been outlined above the complexity of the moberg formations calls for a much more comprehensive investigation program than is typically applied for the conventional regular lava pile stratigraphy, whilst the close proximity to the active volcanic fissures demands risk analysis with scenarios never before being considered for a public project.

## Tunnelling conditions

Even if and when literally every meter of an actual tunnel route have been thoroughly covered by reliable investigations, it is expected that the probability is high that long sections of the tunnel will have to encounter very poor tunnelling conditions.

According to the information that we have received and as per our understanding of the prevailing ground conditions along an assumed tunnel alignment, the tunnel excavation may be approached by 3 different methodologies. These would be as follows:

1. For the first part of the tunnel, starting at Heimaey and reaching approximately to the 6,5km mark on the longitudinal section in Figure 1, a shielded TBM, or even an EPB would be required to be feasible to tackle the adverse and poor rock mass conditions expected to be encountered in this part of the sub sea crossing. Conventional Drill & Blast excavation is considered technically as an infeasible tunnelling method in this section of the tunnel. The total length of this section is approximately 8km. A comparison to the Great Belt project may be relevant for certain parts of the tunnel within these 8km.
2. For the rock tunnel from the 6.5km mark on the longitudinal section in Figure 1 and towards the mainland, conventional Drill & Blast excavation technique may be feasible, concluding an approximate 10km length. Alternatively a double shield hard rock TBM capable of doing both closed and open mode tunnelling could be feasible.
3. From surface at Kross on the mainland to reach rock at some 40 to 50m depth an 800-1000m long section is required which probably may be built by use of an EPB (Earth Pressure Balance machine) in closed mode, or by building inside a complete diaphragm wall shaped as a box or a vortex in a barrel.
4. An open hard rock TBM is most probably an unrealistic tunnelling method for all sections of the tunnel.

It might be possible to construct tunnels in such adverse rock mass conditions, however severe cost and time consuming precautions have to be anticipated and dealt with properly. In the following a close-up on the tunnelling challenges are presented, for conventional Drill & Blast method as well as TBM-excavation.

- For the Drill & Blast method, the following aspects need to be addressed:
  - Rock grouting techniques at the state-of-the-art level of technology, and probably beyond, combined with best practice experienced today, including also grouting techniques used in soil like tub-à-manchettes. Challenges in achieving a safe result are associated with extensive patterns of drilling, stability of groutholes and to get a sufficient distribution of grout into a mix of open veins, fine joints and permeable strata, struggling with more than 200 m of static water pressure and low confinement stress in the rock mass.
  - In the kind of ground conditions as indicated above, successful pre-grouting will be compulsory not only to control leakage into the tunnel, but also for enhanced stand-up time and as a safety against destructive erosion and subsequent tunnel collapse.
  - Rock support measures need to include methods and technologies that are normally relevant for soil tunnelling (or extremely poor rock) such as: sectional excavation, soil anchors, ground freezing, closed ring support including the invert, cast-in-place concrete lining designed to carry full hydrostatic water pressure.

- Pre-cautionary measures and contingencies for additional pumping capacities, closing of the tunnel face, evacuation of people and equipment etc.
  - Ventilation of the tunnel to evacuate the exhaust air and get fresh air to the tunnel face up to a length of 10km.
  - Drilling blast holes and keeping blast holes open and stable to enable appropriate charging and ignition of the holes. Accurate drilling in changing ground conditions to maintain efficient blast rounds and to produce a tunnel profile which fulfils the requirements to smoothness and stability of the contour.
- For a shielded tunnel boring machine (TBM) alternative, the following would be required:
    - Shielded machine with the ability to work as earth pressure balance (EPB) with slurry in a closed face mode is the only choice in certain sections e.g. in the sand deposits on the Kross side where a long approach to a rock tunnel is required.
    - A double shield TBM will have the ability to care for full lining as an on-off strategy. It can also be designed to operate in closed face mode. The method with a single shield TBM requires a full segment lining with full water pressure capacity along the entire length.
    - The segments themselves (and all necessary accessories like rubber gaskets etc.) for the lining must be designed to handle the actual static water pressure, as must the compensation grouting of the annular space behind the lining.
    - Excavation with an EPB in these varying ground conditions with more than 200 m of hydraulic water pressure is also on the edge of today's experience. The Hallandsås rail tunnel in Sweden, just resuming excavation again after 8 years of stoppage and method development, may be an example to illustrate this challenge.
    - The machines running in open mode need to be equipped to tackle probing and pre-grouting in a 360 degrees circumference ahead of the tunnel face using the same grouting technology and mix design etc as mentioned above.
    - Capacity of the muck handling arrangement to keep up with the continuous excavation production and carry the muck effectively at the maximum of 10km from the tunnel face.

## **Comparison with other tunnelling projects**

### E-39, the Rogfast sub sea tunnel in Norway

A sub sea road tunnel, the Rogfast tunnel, has been considered in Norway for the Europaveg 39 with a length of 23,6km. The project was presented at the Strait Crossing conference in Bergen in 2001, (Ref. 5).

The project was cost estimated to 2.2billion NOK for single tube with 2/3 lanes and 3.3billion NOK for a dual tube with 2 lanes in each tube, (calculation year is 2001). Assuming a cost escalation of 25% since 2001 the estimates for the Rogfast project arrive at 2,75 billion NOK and 4,1 billion NOK respectively, corresponding to 25,5 billion ISK and 38 billion ISK.

Doing two parallel tubes in this example represents a 50% increase in the project construction cost.

A direct application of these cost figures to the Vestmannaeyjar would neither be relevant nor will it produce a reliable base for a cost estimate. It must be emphasised that the above construction cost estimates for the Rogfast project is based on geological conditions which are typical for this

region in Norway; that is granites and gneissic rock types of good tunnelling quality allowing conventional Drill & Blast tunnelling. These tunnelling conditions must not mistakenly be compared with the prevailing conditions across to Vestmannaeyjar.

### Emergency evacuation

A number of road tunnels have been built in Norway and Scandinavia over the last years according to Norwegian guidelines and current requirements of these guidelines do not include implementation of dedicated emergency exits. However, and as a consequence and an impact of the recent fires in trans-alp tunnels in Central Europe the EU has provided a set of new regulations for road tunnels particularly focusing safety and emergency possibilities. These new regulations are provided in Figure 5 below.

		Traffic ≤ 2 000 vehicles per lane		Traffic > 2 000 vehicles per lane			Additional conditions for implementation to be mandatory, or comments	
		500-1 000 m	> 1 000 m	500-1 000 m	1 000-3 000 m	> 3 000 m		
Structural Measures	2 tubes or more	§ 2.1					Mandatory where a 15-year forecast shows that traffic > 10 000 veh./lane.	
	Gradients ≤ 5 %	§ 2.2	*	*	*	*	Mandatory unless not geographically possible.	
	Emergency walkways	§ 2.3.1						Mandatory where there is no emergency lane.
		§ 2.3.2	*	*	*	*	*	In existing tunnels where there is neither an emergency lane, nor an emergency walkway additional / reinforced measures shall be taken.
	Emergency exits at least every 500 m	§ 2.3.3- § 2.3.9	○	○	*	*	*	Implementation of emergency exits in existing tunnels to be evaluated case-by-case.
	Cross-connections for emergency services at least every 1 500m	§ 2.4.1	○	○/●	○	○/●	●	Mandatory in twin-tube tunnels longer than 1500 m.
	Crossing of the central reserve outside each portal	§ 2.4.2	●	●	●	●	●	Mandatory outside twin- or multi-tube tunnels wherever geographically possible.
	Lay-bys at least every 1 000m	§ 2.5	○	○	○	○/●	○/●	Mandatory in new bi-directional tunnels >1500m without emergency lanes. In existing bi-directional tunnels >1500m depending on analysis. For both new and existing tunnels depending on extra usable tunnel width
	Drainage for flammable and toxic liquids	§ 2.6	*	*	*	*	*	Mandatory where transport of dangerous goods is allowed.
Fire resistance of structures	§ 2.7	●	●	●	●	●	Mandatory where a local collapse can have catastrophic consequences.	

Figure 5. Table from Roads in October 2004

Figure 4 above shows a table which has been extracted from an article in the magazine Roads, issued by PIARC, in October 2004 (Ref. 8). The article describes “The new Directive 2004/54/EC on Road tunnel Safety” and the referred table represents the current trend in road tunnels at the Trans European Road Network (TERN) as far as safety measures are concerned. As can be seen from the figure it may not necessarily be strictly required in these circumstances with an emergency exit or 2 parallel tubes in this case. However, comparing with the Lærdaltunnel in Norway, currently the longest road tunnel in the world, an emergency exit is located at appr. one third of the length from the Lærdal side.

The Rogfast project is designed with a tunnel branching off to an island at the approximate mid-point in the sub sea section. This branch will also serve as an emergency exit contributing significantly to an improved safety level in the project compared to a one tube solution alone.

A possible tunnel to the Vestmannaeyjar may not have the possibility of establishing a similar emergency exit as was the case for the two examples above. The recommended standard on safety

from EU came into effectiveness after the report prepared by Mott MacDonald (Ref. 2). Mott MacDonald recommended in their report that the tunnel should be constructed with an emergency escape being located below the road deck. The bored tunnel would have sufficient space to accommodate such a solution. However, escapees should make their own way out of the tunnel, which in practical terms would mean a good 10km walk and could make this a questionable emergency escape.

During the construction of the tunnel excavation is likely to take place from both sides, however facing the possibility of encountering difficult ground at both sides excavation may take more than what is normally expected for tunnel excavation of 8-12km length. The risk that an emergency situation occurs during construction with the involvement of construction workers might therefore be much higher than is expected for public users during the operation phase of the tunnel. Consequently, a likely scenario is that construction may not, or should not be allowed to take place unless an emergency route has been established for the workers. The only emergency route for the construction phase would be a situation with two parallel tunnels with inter-connections in a given frequency, alternatively an escape tunnel that could be of a smaller cross section.

Conclusively, designing a sub sea road tunnel between the mainland of Iceland and the Vestmannaeyjar may not be recommended without including a twin tube solution that enables sufficient evacuation during construction as well as during operation of the tunnel. A smaller parallel tunnel to room a single carriageway for emergency vehicles and evacuation may not escalate the construction cost to the same level as a solution with twin tubes.

#### Discussion on comparable cost figures

It is not advisable to give even approximate figures for the cost of tunnelling under such uncertain conditions as described above. Given the difficulties and possible challenges indicated for any of the two tunnelling principles at least 3–4 times the cost per meter in a single drive compared to Hvalfjörður tunnel must be expected. Even if pre-cautious Drill & Blast may be feasible in certain sections, the tunnelling advance may become very slow and it is easily envisaged that both cost and time will be severely influenced by frequent stopping incidents. Slow advance (e.g. 20 m/week), thorough grouting, heavy rock support and extensive safety installations may add up to 2mill. ISK per meter tunnel.

Reference can be made to the Oslofjordtunnel and the Bjorøy tunnel where significant problems were encountered in shorter sections of the tunnels enforcing stability measures that never had been experienced in sub sea tunnelling before. These measures included such as soil injection using tub-á-manchettes and a total of 23 weeks were needed to traverse a 38m long section of the Bjorøy tunnel using this technique. For the Oslofjordtunnel a different approach was chosen as ground freezing was performed to pass a weak zone, with a length of appr. 20m. The entire process to excavate safely through the zone took a little less than 2 years. Similar measures cannot be ruled out in larger parts of a tunnel across the Vestmanna sound.

Any cost estimate for a tunnel to Vestmannaeyjar would be associated with great uncertainty. For TBM alternatives (shield tunnelling or EPB) may result in better confidence but the base costs in more favourable conditions will be higher. A completely lined, 9 m diameter tunnel excavated by an advanced, shielded TBM could be in the magnitude of 2,5mill. ISK per meter tunnel, however with expectedly shorter construction time.

The major uncertainty in all cost estimates is associated with the probability and consequence of severe incidents that are causing a halt in the excavation. That should be a main focus of geological considerations and risk analysis.

Taking into account the length of the tunnel to Vestmannaeyjar and the expected prevailing geological conditions a cost estimate should be based only on the TBM technique. To keep the cost estimates on a rough level we would like to address some figures that were presented last year in the Open Session of World Tunnelling Conference in Istanbul focusing mega-projects on fixed links.

One such project is a twin tube 33km long crossing of the Nusantara (Ref. 6) planned to be excavated with TBM. This project was cost estimated at 1,5-2 billion USD, being equivalent to approximately 95-125 billion ISK. This will produce a construction cost for an approximate tunnel length of 18-19km long twin tube tunnel to Vestmannaeyjar in the range of 55-70 billion ISK. In addition the cost associated for the construction of a portal at Kross has been estimated to approximately 5 billion ISK in both (Ref. 1) and (Ref. 2).

Another project being considered recently and that was also presented in the same conference is the Gibraltar Crossing (Ref. 7). A cost estimate of 4 billion Euros for a 38,5km long twin tube tunnel was presented, also planned to be excavated by TBM. This is equivalent to approximately 140 billion ISK for a twin tube tunnel to Vestmannaeyjar.

It is clear from the above figures that cost for such projects are difficult to estimate and consequently significant variations occur. Further, the above project references may have other requirements on tunnel installations, different geological challenges, project specifications, local constrictions etc. than would apply to a tunnel to Vestmannaeyjar. Important in this comparison is that the basis for the Norwegian cost figures is not applicable as they are referring to a different concept than will apply for a potential tunnel to the Vestmannaeyjar. Therefore other references need to be considered that are based on comparable ground conditions and tunnelling concept. The figures arrived at in the Mott MacDonald report (Ref. 2) and those figures presented above can be considered as being in the same magnitude and also being much more realistic and relevant than the experience from Norwegian tunnelling projects.

## Conclusions

The basis for evaluation of a project proposal of this kind must be significantly improved and should be much more concrete before it is possible to provide any committing recommendations on the feasibility of this tunnelling project and make robust cost estimates. Given the factors we are able to consider, it is however, possible to present some preliminary conclusions, which we feel can assist in the discussions on a further development strategy.

We feel even more compelled to do so, as it has been referred to other voices from the Norwegian tunnelling industry as a support for, in our opinion, a far too optimistic evaluation of the project.

It is easy to become intrigued by a tunnel project like this, as it has the potential of becoming both famous for its challenges and, if a success, a boost in moving state-of-the-art of tunnelling forward.

On the negative side, which needs to be considered thoroughly before any major investment is spent on expensive and comprehensive pre-investigations and financial analyses, we feel compelled to state the following:

- investigations will have to be of an unprecedented amount, comprehensiveness and cost before meaningful results (a robust basis for decision to build) can be achieved,
- risk analysis need to consider the probability and consequences of a volcanic eruption and/or intense earthquake activity along active fissures,
- substantial uncertainty prevails as to the construction method and technology, construction time and costs, contractual basis and feasibility of construction,
- tunnelling conditions will be severely more difficult than experienced in any other sub sea tunnels in Norway, Iceland and in the Faroe Islands and thus lead to other construction methods,
- cost figures from Nordic sub sea tunnel projects would be irrelevant references and significantly higher construction cost must be anticipated,
- safety aspects during construction and operation will call for a solution with two parallel tubes and frequent inter-connections, and,
- tunnel operation cost will be considerable as well, especially compared to the actual traffic load that could be expected.

Conclusively, a sub sea tunnel to the Vestmannaeyjar will be on the edge of, if not beyond the present tunnelling technology. The existing information on the geological conditions indicates that construction methods, time and cost estimate for this tunnel cannot be compared with other sub sea tunnel projects in Scandinavia. Based on current knowledge it is not possible to verify that the work can be performed in accordance with standard tunnelling procedures such as known from the Hvalfjörður tunnel and similar sub sea tunnels in the Faroe Islands.

Applying reference costs from projects like the Nusantara and Gibraltar crossings would yield cost estimates ranging from 60-75 and up to 140 billion ISK for a 18-19km tunnel to Heimaey. Thus, an estimate on construction cost in the range of 100 billion ISK may at this stage be a realistic magnitude of costs for a tunnel to fulfil relevant requirements on safety and installations including two parallel tunnel tubes being excavated with TBM. If future detailed investigations yield ground conditions that are more favourable, the costs may possibly be reduced. If adequate safety can be obtained by a single tube the indicated cost may be reduced to approximately 70 billion ISK.

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