EARTHQUAKE HAZARD AND CRUSTAL MOVEMENTS IN THE HVALFJÖRÐUR AREA

A preliminary study regarding the proposed Hvalfjörður tunnel site

Prepared for Spölfur Ltd

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INTRODUCTION

Iceland is on the Mid-Atlantic plate boundary, between the North-American and Eurasian lithosphere plates. The site of the proposed tunnel under the fjord Hvalfjörður in SW-Iceland is not far away from the most tectonically active parts of the country. Therefore, the question of earthquake hazards has to be addressed in the design and construction of the tunnel.

The earthquake induced effects on tunnels depend on many factors, e.g. the magnitude, hypocentral distance and source mechanism of the earthquake, the wave motion of the bedrock, the condition of the rock mass, the number of joints and fault systems crossing the tunnel - their direction as well as their condition - and the cross section of the tunnel and its support system.

This report concerns the earthquake hazard at the site of the proposed Hvalfjörður tunnel. A general account is given of possible earthquake sources that are likely to have effect in the Hvalfjörður area and the frequency of earthquake occurrence is estimated. The probable earthquake effects are assessed in terms of maximum particle acceleration and velocity, as well as Modified Mercalli intensity. It emerges that large earthquakes in the plate boundary areas are not likely to cause significant damage to the tunnel. A large intraplate earthquake \( M \geq 4\frac{1}{2} \) in the vicinity of the tunnel is likely to cause damage. The probability of such an event is lower than that of plate boundary events, but warrants further risk assessment.

SEISMIC HAZARD

Some of the most active tectonic regions in Iceland, linked to the boundary between the North-American plate and the Eurasian plate, are in the vicinity of the proposed Hvalfjörður tunnel. The seismicity is mainly confined to the Reykjanes Peninsula and the South Iceland Seismic Zone, but some activity occurs in the Western Volcanic Zone. In addition, intraplate earthquakes in the western part of the country are of importance and cannot be ruled out (Einarsson, 1989; 1991a).
In the following, the seismicity of the regions mentioned above will be discussed and the maximum earthquake intensity at the construction site will be assessed, as well as the probable peak ground acceleration and velocity. In estimating the intensity, the attenuation formula of Páll Halldórsson (1992) is used. Estimates of the peak values of ground acceleration and velocity are based on data obtained from the strong ground motion instrumentation network operated by the Engineering Research Institute of the University of Iceland (Sighjörnsson and Baldvinsson, 1992). Assessment of potential damage is obtained using data and suggested damage levels of rock tunnels by Dowding and Rozen (1978) (ATC-13, 1985; Brady and Brown, 1993).

The Reykjanes Peninsula: The plate boundary is marked by a narrow seismic zone entering the peninsula near the tip of Reykjanes, running along the southern part of it to the east, where it meets the South Iceland Seismic Zone and the Western Volcanic Zone near the Hengill central volcano. The largest earthquakes occur in the eastern part of the peninsula, between Brennisteinsfjöll and Hellsheidi. They can reach a magnitude of 6 to 6½. Such events have occurred twice this century, in 1929 and 1968. On the average, they seem to occur every 30 to 40 years. The expected intensity of such an earthquake at the site of the proposed Hvalfjörður tunnel is about VII on the Modified Mercalli intensity scale. The expected peak ground acceleration is approximately 10% g, where g denotes the acceleration of gravity, and the peak ground acceleration will probably not exceed 25% g. The peak ground velocity can be expected to be around 15 cm/s.

Earthquakes originating on the Reykjanes Peninsula could cause some minor damage in the proposed tunnel, especially where it crosses fractures and layer interfaces.

The South Iceland Seismic Zone: In the southern part of Iceland the divergence between the two plates is accommodated by two subparallel rift zones, the Western and the Eastern Volcanic Zones. In the south, the gap between them is bridged by the South Iceland Seismic Zone (SISZ), which takes up the transform motion between the Reykjanes Ridge and the Eastern Volcanic Zone. Large earthquakes originate in an elongated region between Hengill in the west and Torfajökull in the east. In the western part of the SISZ (in Ölfus), earthquakes of magnitude 6 to 6½ seem to take place every 30 to 40 years, while in the eastern part (in Land,
Holt and Rangárvellir), earthquakes of magnitude 7 can occur twice every century (Stefánsson and Halldórsson, 1988). At the site of the proposed tunnel, the intensity of an earthquake originating in the SISZ could be VI or VII on the Modified Mercalli intensity scale. The expected peak ground acceleration in such an event is 5-7% g, and it will probably not exceed 15% g.

Earthquakes originating in the South Iceland Seismic Zone will probably not have any damaging effect on the proposed Hvalfjörður tunnel.

*The Western Volcanic Zone:* Even though the Western Volcanic Zone, extending from Hengill north-east towards the glacier Langjökull, seems to be a dying rift zone, some divergence is still taking place there. This divergence is accompanied by some earthquake activity. During the last decade, earthquakes with epicentres between the mountain Skjáldsheidiur and Langjökull have reached magnitudes of 4.5 and 5.1. The possibility of larger earthquakes in this area, probably up to magnitude 5½ to 6, cannot be ruled out. The frequency of such events is not known, but it is not unreasonable to expect them to occur 2 or 3 times each century. At the site of the proposed tunnel, the intensity of such events could be approximately VI on the Modified Mercalli intensity scale. The peak ground acceleration is expected to be around 5% g, and probably less than 13% g.

Earthquakes originating in the Western Volcanic Zone will probably not have any damaging effect on the proposed Hvalfjörður tunnel.

*Intraplate earthquakes:* Most intraplate earthquakes in Iceland occur in two separate regions. One is off the east and south-east coast, and is not of interest in this study. The other one is west of the Western Volcanic Zone (Einarsson, 1989). Best known of these latter earthquakes are the Borgarfjörður events in 1974 (Einarsson et al., 1977), with a maximum magnitude of approximately 6. In addition to these events, some smaller events have been instrumentally detected in the western part of the country, covering the area between the Tjörnes Fracture Zone in the north and the Reykjanes Peninsula in the south. The reason for the intraplate earthquakes in western Iceland is not quite known. The shape of the North-American plate, however, could play an important role in the explanation, as it forms a structurally weak tongue to the east (Fig. 2).
The probability of an intraplate earthquake of magnitude 6 around the tunnel site is likely to be low but is not known. More investigation is needed in order to put such probability estimates forward. However, should such an event occur within a 20 km radius, its intensity at the tunnel site could be more than VIII on the Modified Mercalli intensity scale, and the expected peak ground acceleration is of the order of 30 to 40% g, but it could get as high as 100% g. Furthermore, the expected peak ground velocity is over 50 cm/s. Slip on faults may be expected, from a few cm to a few tens of cm. Thus, it may cause damage - even considerable damage - to the proposed tunnel.

The lowest magnitude intraplate earthquake that could possibly cause damage to the tunnel has also been assessed. According to Dowding and Rozen (1978) the lowest acceleration that could cause minor damage is slightly less than 20 % g. This corresponds to a 4.5 magnitude earthquake with a source immediately below the tunnel (Sigbjörnsson and Baldvinsson, 1992).

It should be pointed out, that the probability of damage in earthquakes increases if the proposed tunnel is driven through fault zones or different rock layers with abrupt stiffness changes. Furthermore, distant earthquakes can cause deformation and differential slip on possible fault planes. Some fault planes in the vicinity of the proposed tunnel could even be potential sources of intraplate earthquakes.

It is therefore clear, that earthquake hazards have to be considered in the design and construction of the proposed Hvalfjörður tunnel.

RECOMMENDATIONS

From the above considerations, one can draw the conclusion that the most hazardous seismic events for the proposed Hvalfjörður tunnel are intraplate earthquakes in the western part of Iceland. The effect of such events could be excessive strains and differential slip on possible fault planes. Therefore, the following research topics are recommended:

*Intraplate earthquakes in western Iceland:* 1) Existing data on intraplate earthquakes should be examined, both along the Mid-Atlantic Ridge as a whole and in the western part of Iceland
in particular, in order to assess the frequency, magnitude and location of such events. 2) By establishing seismic stations in the Hvalfjörður area, the locations and frequency of minor earthquakes can be estimated more accurately. This could give some information about the strain accumulation in the area as well as the location of possible weaknesses. 3) The deformation of the crust - hence, the strain accumulation - can be measured with geodetic methods - such as the GPS-technique. A coarse geodetic network was established in the Hvalfjörður area during the years 1986-1989 (Einarsson, 1991b). Remeasurements of this network could give some bounds on the rate of strain accumulation. 4) Thórarinsson et al. (1989) identified cross-grain magnetic and gravitational anomalies crossing Hvalfjörður, possibly indicating zones of weakness in the crust (Fig. 3). The significance of these anomalies should be studied further.

The geology of the area: 1) The proposed tunnel is oriented perpendicular to the main dike and fault direction in the area and seismic hazard is mainly associated with such discontinuities. These planes of weakness are likely sites of possible future damage due to differential movements. It is therefore important to identify location of layer interfaces, dikes and faults in the profile of the proposed tunnel so a proper support systems in these places can be designed accordingly. 2) Existing reflection profiles of the sediments in the fjord may reveal postglacial slip on faults. 3) Study of slickensides on fault surfaces along the coast and in the tunnel may show evidence of renewed activity on the faults after they left the active plate boundary region.

Tunnel support systems: Rock tunnels constructed in earthquake prone regions around the world should be surveyed. When importing foreign experience it should be kept in mind, however, that the Icelandic rock mass is quite unique.

Monitoring: 1) After the construction of the tunnel, some monitoring of crustal movements should be maintained. It is recommended, that at least one automatic seismographic station should be established and connected to the network of the Icelandic Meteorological Agency. 2) Repeated GPS-measurements on a dense geodetic network in the area should be carried out - say, every three years.
FINAL REMARKS

The proposed Hvalfjörður tunnel is a huge construction project. There is no Icelandic experience regarding the construction of rock tunnels under the sea, and experience from abroad does not apply without modifications due to different geological conditions. This project is not only huge, but also very unusual, which calls for extra care in preparations.

REFERENCES

ATC-13, Earthquake damage evaluation data for California (1985), Applied Technology Council, California.


Fig. 1. Epicentres of earthquakes in Iceland 1982-1985. Earthquakes of magnitude greater than 2 are shown (Einarsson, 1989).
Fig. 2. Intraplate earthquakes in Iceland 1930-1987, plate boundaries and volcanic zones (Einarsson, 1989).
Fig. 3. The cross-grain structures in SW-Iceland. The hatched areas show filtered gravity anomalies exceeding 4 milligals. The shaded areas show filtered magnetic anomalies below -200 nanotesla. The broken line circumscribes the area where the depth to seismic layer 3 is less than 2.5 km (Thórarinsson et al., 1989).