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Earthquakes and faults in the Kárahnjúkar area

Review of hazards and recommended further studies

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Abstract:

The report gives a brief qualitative review of hazards in the Kárahnjúkar area due to earthquakes and faults, taking into consideration relevant new geological observations that indicate Holocene faulting in the area. Although the Kárahnjúkar area is currently seismically quiet, stress and strain fields in the area may change and revive seismic activity.. Faulting may be triggered due to increased pore pressure due to the establishsment of Hálslón. A significant normal faulting near-field earthquake should be given due consideration. Hazards from opening of fractures in response to increased pore pressure are considered significant as well.

Keywords: Kárahnjúkar, Earthquakes, faults

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March 2005

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Table of content

1. Introduction

This report presents a brief review of hazards in the Kárahnjukar area due to earthquakes and faults, taking into consideration relevant new geological observations. Its purpose is to review hazards in the area, in particular by considering the implications of the latest information on tectonics of the area, as well as discussing what efforts are recommended to improve the understanding of these hazards. This document is prepared in accordance with a request from Landsvirkjun at a meeting on January 19, 2005, that "geophysical and earthquake specialists under the leadership of Freysteinn Sigmundsson will review previous and new documents and other pertinent information on hazards from earthquakes and faults, and submit to Landsvirkjun their findings and evaluation in a memorandum". The scope of the work, as well as the conclusions derived, is restricted because of short time frame, and limited present knowledge about the tectonic behavior of the area. This report approaches the hazards in a qualitative way but with limited quantitative assessment or an attempt to assess the frequency or likelihood of the different scenarios outlined. The report brings together the overall views and opinions of the different authors (without committing their home institutes in any way), but does not ensure the individual authors consensus on all the details presented in the text

2. Seismic safety of dams and estimates of hazards

2.1 Earthquake Performance of Large Dams

The field of earthquake safety of dams is still under constant development and there are still considerable uncertainties about the detailed behaviour of dams during earthquakes. However, new lessons are learned from each strong earthquake through the observed behaviour and damages, as well as from strong motion records of instrumented dams.

Wieland (2003) has summarized the historical earthquake behaviour of large dams as follows:

(i) General behaviour

- Earthquakes have damaged very few dams.
- Only about a dozen dams are known to have failed – primarily tailings and hydraulic fill dams.
- Only a small number of other embankment or gravity dams of significant size have been damaged.

(ii) Observed earthquake performance of embankment dams

- Modern well-built embankment dams have performed well.
- Compacted clay dams have performed well.
- Rock fill and concrete-faced rock fill dams have performed well.
- Insufficiently compacted sand or silt dams and tailings and hydraulic fill dams have performed poorly.

(iii) Observed earthquake performance of large concrete dams

- Concrete arch dams have performed very well, but few have been exposed to very strong ground shaking.
- Concrete gravity and buttress dams have generally performed well.
- Shih-Kang dam experience (1999 Chi-Chi earthquake, Taiwan) demonstrated difficulties in designing concrete dams to accommodate large fault movements.

Further, according to Ozkan (1998), Omachi and Kuwano (1994) have concluded that:

- Any well-built dam can withstand moderate earthquake shaking, with peak accelerations of about 0.2 *g* and more without detrimental effects.
- Dams constructed of clay soils on clay or on rock foundations withstand extremely strong ground shaking ranging from 0.35 to 0.8 *g* from a magnitude 8.25 earthquake with no apparent damage.
- Dams constructed of saturated cohesion less soils and subjected to strong ground shaking, a primary cause of damage or failure is the build-up of pore water pressures in the embankment and possible loss of strength may accrue as a result of these pore pressures.
- The fact that a number of failures occurred in the 24 h after the earthquake suggests that piping through cracks resulting from the earthquake shaking may be responsible for the failure.

It should be noted that the majority of the older dams were built using methods of seismic analysis and seismic design criteria, which, today, are considered as obsolete or outdated. In many cases, it is not known if an old dam complies with current seismic safety guidelines, which are stricter than those used in the past. This problem has been recognized and several countries are looking into the seismic safety of existing dams.

Building a dam across an active fault should be avoided, if possible. However, an alternative site may not be available and a conservatively designed dam may need to be considered. Many dams are in fact built across streams or rivers that follow existing fault traces. Even though such faults are not necessarily active, the potential for differential movement across the dam foundation must be taken seriously and investigated. A few examples of dams built across active faults are described by Sherard *et al.* (1974) and Allen and Cluff (2000).

In addition to the risk of sudden fault rupture, fault creep may also cause distress within a dam. Fault creep is a gradual, continuous, relative displacement that occurs generally at a low rate of slip. Fault creep has been observed across Bajina Basta and Lipovica dams in Yugoslavia (Bozovic and Markovic, 1999) but is considered to be a sufficiently rare phenomenon that can usually be dismissed in seismic studies for dam projects (Allen and Cluff, 2000).

The Committee on Seismic Aspects of Dam Design (ICOLD), which comprises dam and earthquake experts from about 25 different countries, has published several bulletins that represent the state-of-practice in the field of seismic design and earthquake safety evaluation of existing dams. Case studies on the effects of earthquakes on large dams can be found in ICOLD Bulletin 120 (ICOLD, 2001).

2.2 On the seismic design criteria for the Kárahnjúkar Hydroelectric Project

The seismic design criteria applied by the design teams is presented in chapter 7: Synopsis – Seismic design criteria, in the Kárahnjúkar Dam Design report and in Appendix 5: Desjarárstífla – Seismic analysis (KEJV/Harza, 2003)

The ICOLD approach mentioned before is followed in Table 7.2-6 (KEJV/Harza, 2003) where a magnitude and epicentral distance for various events are defined.

Mainly three earthquake scenarios are considered:

(i) Effects of earthquakes along the active plate boundary in Iceland, particular consideration is given to earthquakes in the Tjörnes Fracture Zone with magnitude up to M_s 7.2;

(ii) earthquakes in nearby volcanic areas with magnitude up to M_s 6.5 (at distances as short as 15 to 20 km from Kárahnjúkar);

(iii) and reservoir triggered earthquakes of magnitude M_s 4 (Table 7.2-4, KEJV/Harza, 2003). In the seismic design, the possibility of larger reservoir triggered earthquakes up to magnitude 5 was considered (Fjóla G. Sigtryggsdóttir, personal communication, 2005).

The reservoir-triggered earthquake is defined based on ICOLD Bulletin 46, considering the existing stress regime (assumed low), the weakest zones (lineaments) and speed of reservoir filling (KEJV/HARZA, 2003, chapter 7.7).

The peak ground accelerations considered are in the range between 2.6% g for scenario (i) (Ragnar Sigbjörnsson, 2000) and 0.5% g for scenario (iii) (KEJV/VST, 2003, Table A.5.1-1). Scenario (ii) is largely based on time series recorded in earthquakes of magnitude 6.5 in South Iceland in June 2000, scaled to a peak ground acceleration of 26% g.

It should be noted that peak ground acceleration of 26% g, which has been considered for the Kárahnjúkar site, is comparable to the design PGA used for hydroelectric projects in the Tungnár area, which lies closer to a more seismically active area.

2.3. Recorded earthquake activity in the past in the Kárahnjúkar area and adjacent volcanic systems

Eventual future earthquake and faulting events in the immediate vicinity of the Kárahnjúkar area and in adjacent volcanic systems are relevant for the Kárahnjúkar hydroelectric project. The Kárahnjúkar area itself appears, however, to have been quiet for the last few decades (period of reliable recording) with the nearest earthquake activity being in the Kverkfjöll and Askja volcanic systems. At Kverkfjöll, the earthquakes cluster at the center of the system, at Mt. Kverkfjöll. In the Askja system much more activity has been recorded, both in the Askja caldera, as well as in the Askja fissure swarm. A peculiar seismicity occurs also at the eastern border, and east of the Askja fissure swarm, in the area of Herdubreið and Herðubreiðartögl. This seismic area is in a similar tectonic setting relative to the Askja central volcano, as the Kárahnjúkar area is against the Kverkfjöll central volcano, close to and outside their associated fissure swarms.

A network of analog seismic stations was installed in North Iceland, beginning in 1974. With a detection threshold for earthquakes in the Kárahnjúkar area and adjacent volcanic systems of ~M2.5, no earthquakes have been recorded there. A three-component digital seismic station was installed in 1998 at Aðalból in E-Iceland, close to Kárahnjúkar, as a part of the present digital seismic network, SIL, operated by Veðurstofa Íslands. By this the detection threshold was lowered to ~M1. Numerous explosions associated with construction in the Kárahnjúkar area have been detected, in addition to several events ~M1 (including one on 8 February 2001) that have not been confirmed to be explosions. In the fall of 2004, three new stations were installed in the Kárahnjúkar area as a part of the seismic monitoring program, in order to increase the sensitivity of the system to at least ~M0. It is clear that the area is characterized by minor or no seismicity in the last decades.

An overview of seismicity 1982-1985 is given by Einarsson and Sæmundsson (1987), for 1975-1985 by Björnsson and Einarsson (1990), for 1991-2003 by Jakobsdóttir *et al.* (2002), Þorbjarnardóttir *et al.* (2003a, 2003b), and Guðmundsson *et al.* (2004).

2.4 Crustal subsidence by the Hálslón reservoir

Hálsón when filled will contain 2.4 km^3 of water. Crustal subsidence because of this load has been estimated to be about 30 cm, depending on a number of assumptions in model calculations (Sigmundsson, 2002).

2.5 Concern regarding limited geophysical research in the Kárahnjúkar area

Some scientists have expressed their concern regarding the limited scope of geophysical research of Kárahnjúkar and adjacent areas in the preparatory phase of the project, as well as concern about the area being more hazardous than stated. Grímur Björnsson

(2002) concludes that it is incorrect that the bedrock in the Kárahnjúkar area is well suited as a base for dams as stated by Landsvirkjun (2001, p. 31) "Að mati tæknimanna hentar bergið á stíflustæðinu vel sem grunnur fyrir þær [Fyrirhugaðar stíflur við Kárahnjúka]". Guðmundur Sigvaldason (2003), a leading volcanologist, also expressed his concern regarding building the Kárahnjúkar dam in a fault zone.

3. Experience from other areas in Iceland and around the world

3.1. Reservoir triggered earthquakes and faulting in other areas in Iceland

Confirmed reservoir triggered earthquakes are not known in Iceland as far as the authors know. However, previous reservoirs formed are much smaller than Hálslón reservoir will be. The largest of previous man-made reservoirs is the volume increase of Lake Þórisvatn, as a result of increase in water level from 571 to 579 m, associated with hydro-electrical projects in the Tungnaár-Þjórsár area since 1972. That corresponds to 0.65 km^3 increase in water volume, or about 27% of the volume of the Hálslón reservoir. Size of the Blöndulón reservoir is 0.5 km^3 and the third largest reservoir is Hágöngulón, with a volume of 0.32 km^3.

Seismic stations were installed in the Tungnaár-Þjórsár area in 1975, and since then there has been no significant earthquake activity in the area, except for a few small earthquakes under Mt. Búðarháls. There seems to be no connection between these earthquakes and the establishment of reservoirs in the area.

At the Blöndulón reservoir, four earthquakes have been recorded: An M2.2 event 1 km east of the reservoir in March 1991, an M1.4 event 1 km south of the reservoir in June 2002, on October 27, 2004, two M~1.5 earthquakes occurred under the reservoir. All the events were shallow. The earthquakes under the reservoir in October followed increased earthquake activity earlier in 2004, located 10 km further south, on a NNE trending lineament near Guðlaugstungur. This lineament may extend all the way to Hveravellir.

Reservoir triggered aseismic faulting on the other hand, has occurred in Iceland. Opening of a tectonic fracture occurred at the Langalda dam in 1971 in the Tungná area, draining a test reservoir that was 8 m deep and 1.5 km^2 in area (Tómasson, 1975; 1976). A fracture system under the Landalda test reservoir was influenced. Tómasson (1975, 1976) reports that "some of the fractures are evidently old, having old fillings on their inside walls, which when loosing their support have caved in more or less. The remaining fracture fillings often indicate a divergence of 20 cm or so. The broadest fracture is about 70 cm wide of which nearly 50 cm constitute old filling". Groundwater level ~20 meters below the surface, and a low horizontal stress field perpendicular to an old normal fault that opened up, are considered to be influential causes. Under these conditions the lake pressure appears to have opened the fracture at its weakest point. Then hydrostatic pressure inside the fracture became higher than the horizontal stress perpendicular to the fault plane, which opened up the fracture.

Further studies at Langalda are described by Tómasson (1975, 1976) and Tómasson *et al.* (1976). An evaluation of early results conducted by EWI/Virkir (1971) concluded that earthquakes did not open the fault system in April 1971 at Langalda, and it is impossible that the water load of Langalda Lake caused the dislocation. We, as Tómasson *et al.* (1976) agree with the first of these conclusions. There is no clear evidence for earthquake activity associated with fracture movements at Langalda. Later experience in Iceland demonstrates, however, that aseismic movement can occur (see e.g, Kleifarvatn discussion in chapter 3.2). It is considered likely that this may be the case for the Langalda fractures. We have no reservation against the conclusion of Tómasson (1975, 1976) presented in the above paragraph, that at Langalda hydrostatic pressure in a fracture higher than the horizontal stress perpendicular to a fault plane caused fracture opening.

3.2. Hydrological effects on earthquakes and volcanic eruptions in Iceland

Earthquake triggering associated with hydrological loading is inferred in one area in Iceland in the past decades, under Goðabunga at the Mýrdalsjökull ice cap. A yearly cycle in earthquake activity is inferred to be occurring there in response to increased pore pressure in autumns reducing friction on fault planes, superimposed on prevailing high stress levels (Einarsson and Brandsdóttir, 2000; Þorbjarnardottir *et al.*, 2003a and b).

Release of overburden pressure associated with jökulhlaups (glacial outburst floods) from the Grímsvötn caldera lake appears to be a trigger for a number of eruptions of the Grímsvötn volcano, including the most recent eruption in 2004.

The Grímsvötn and Katla volcanoes are two of the most active volcanoes in Iceland, with molten magma present at shallow depth. Their crustal structure is very different than that at Kárahnjúkar.

Faulting at Lake Kleifarvatn on June 17, 2000 provides an example of triggered strike-slip faulting, and associated lake drainage. An M_w 6.5 earthquake in the South Iceland seismic zone then triggered widespread earthquake activity along the plate boundary west of the main shock. The largest triggered event was a slow M_w 5.8 earthquake (geodetic moment $M_o \sim 6\text{-}7 \times 10^{17}$ Nm) at Kleifarvatn, with part of the slip occurring aseismically (Pagli *et al.*, 2003; Arnadottir *et al.*, 2004). A major hydrological effect of this event was associated with opening of a fissure on the lake bed that drained water, lowering the lake level by 4 m over 1.5 years (Clifton *et al.*, 2003).

3.3. Reservoir triggered earthquakes in other areas of the world

Reservoir filling modifies the stress regime within crustal layers and reduces the effective shear strength of the rock mass, and pre-existing faulted rock with a high *in situ* state of stress can be brought to slip by the reservoir impoundment. Most reservoir-induced seismic events have occurred in areas affected by Quaternary faulting. Hence, earthquakes there have most likely been *triggered* rather than *induced* by a reservoir, and such terminology is now considered appropriate (USCOLD, 1997). While the possibility of reservoir-triggered earthquakes should be considered for any reservoir deeper than 80 to 100 m, experience suggests that the maximum reservoir-triggered earthquake should not exceed the design earthquake that must otherwise be specified for any site located within an area of recognized potential seismic activity. For other areas of the world, the likelihood of a reservoir-triggered earthquake being associated with significant surface fault displacement has been considered low (Allen and Cluff, 2000).

Around the world, reservoir triggered seismicity is frequent. A summary by Gupta (2002) lists 95 sites globally with reported reservoir triggered seismicity. At most of these sites, the maximum size of triggered activity is less than M5. However, for 14 sites magnitude of triggered earthquakes has exceeded M5, with the largest recorded earthquake being $M_s6.3$ ($M_w6.6$). It occurred at the Koyna Dam in Western India in 1967. Maximum recorded acceleration was 63% g. With no known seismicity in the area before the construction of the dam, that area has been the site of most extensive reservoir triggered seismicity in the world. In the last four decades prior to 2003, 18 earthquakes, M≥5 and thousands of smaller events have occurred in a small area of 15 x 30 km^2 (Gupta, 2002; Chadha *et al.*, 2003). At Koyna, the reservoir volume is 2.8 km^3 and the dam height is 103 m.

4. Summary of new geological findings in the Kárahnjúkar area

Important new findings include i) the observation of Holocene faulting in the area at the Sauðárdalur fault and the suggestion that this fault is an extremity fault of the Kverkfjöll fissure swarm ii) stronger apparent relation between geothermal activity and faulting in the area, iii) more extensive strike-slip faulting at the Kárahnjúkar dam site (Ágúst Guðmundsson and Jóhann Helgason, 2004; Kristján Sæmundsson and Haukur Jóhannesson, 2005).

Previous studies on the tectonics of the area include the work of Helgason (2002) and Guðmundsson (1996).

5. Normal faults in the Kárahnjúkar area

5.1 The nature of earthquake scenarios on the fault in Sauðárdalur

The Sauðárdalur fault is the only fault in the area known to have moved in the Holocene. The current mapped length of the normal fault is 12-14 km (Sæmundsson and Jóhannsson, 2005), but it may be well be longer (Sæmundsson, personal communication, February, 2005). The length and nature of the fault needs further investigation.

If its mapped horizontal extent fails through the seismogenic crust, the effected fault plane would be of a similar dimension as the faults that broke in the South Iceland Seismic Zone on June 17 and 21, 2000 (Clifton and Einarsson, 2005). These faults are taken as an analogy here, because they have been well studied and are of similar dimensions as the Sauðárdalur fault. However, it should to be kept in mind that they are strike-slip faults, whereas the Sauðárdalur fault is a normal fault. Aftershocks show that the June 17th fault is near vertical, 16.5 km long, and extends down to 10 km depth. The

June 21 fault is 16.5 km long, near vertical, and extends down to 6 km at its northern end, deepening to 9 km at the southern end (Hjaltadóttir and Vogfjord, 2004). Models based on geodetic data for distributed slip on the faults show a maximum slip over 2 meters above 6 km depth tapering off to the edges and at greater depth (e.g., Pedersen *et al.*, 2003). These models indicate very little slip below 9 km depth.

The Sauðárdalur fault is considered to be a growth fault that has formed in a series of events leading to the cumulative offset on the fault, eventually associated with rifting events in the Kverkfjöll fissure swarm. The current size of its fault plane is considered to govern the maximum faulting event on it. It is estimated as an event corresponding to failure along the current mapped length (here set as 12 km), and throughout the seismogenic crust, here estimated to extend down to 9 km depth. Measured offset on the fault amounts to ~2.6 m, and is inferred to have slipped three times in the Holocene (Sæmundsson and Jóhannesson, 2005). We estimate average slip associated with a maximum faulting event on the plane to correspond to about a third of the measured total offset, or 0.9 meters. Seismic moment of such an event would be:

$$M_o = \mu \times \text{slip} \times \text{fault area} = 3\times10^{18}\,\text{Nm} \qquad (1)$$

assuming shear modulus, μ, of 30 GPa.

Seismicity associated with such an event is uncertain. Based on behaviour of normal faults in the fissure swarms of Iceland and recent observations, the moment in a faulting event might be released in series of earthquakes, or even aseismically. The rupture of the whole fault plane in a single earthquake can, however, not be ruled out. Such an earthquake is here termed the maximum sized earthquake and its magnitude can be determined from the moment-magnitude relation:

$$M_w = \left(\frac{2}{3}\log M_0\right) - 6.03 \qquad (2)$$

One finds M_w = 6.3. The probability of a normal faulting event breaking along the complete mapped length of the Sauðárdalur fault is considered small. Furthermore, under failure along the entire mapped length of the fault, part of the stored energy might be released aseismically (see chapter 3.2).

A different scenario would be release of the moment in a series of significantly smaller earthquakes, each taking place on a more limited plane. The smaller the earthquakes, the larger their number in order to accommodate the seismic moment ($\approx 3\times10^{18}\,\text{Nm}$) of the maximum faulting event. For example, a series of ten M_w = 5.6 earthquakes would accommodate the same moment, as well as a series of one hundred M_w = 4.9 earthquakes. Such failure of the Sauðárdalur fault in a series of earthquakes could lead to longer duration of earthquake shaking than if the fault would break in a single event, all depending on temporal spacing between the smaller earthquakes. Furthermore, as mentioned above, part of the fault slip may occur aseismically. In any case, due to the size of the Sauðárdalur fault and the measured cumulative offset, the maximum faulting event is considered to have seismic moment $\approx 3\times10^{18}\,\text{Nm}$.

It is pointed out by Sæmundsson and Jóhannesson (2005) that the estimated time of last slip on the Sauðárdalur fault, 3-4000 years ago, correlates in time with stepwise draining of the former Hálslón lake some 4000 years ago (Harðardóttir *et al.*, 2003). This implies the possibility of a link between these two events, opening the question of whether stress change associated with the draining of the former Hálslón could have triggered fault slip, or vice versa, if faulting triggered lake drainage.

5.2. Fissure swarms, rifting episodes, and normal faulting

The best documented rifting episode in Iceland is the Krafla rifting episode from 1975-1984. Seismic activity during the rifting episode is documented by Einarsson (1991). Activity in the Krafla fissure swarm during rifting events was characterized by numerous small earthquakes of up to M4.5, and volcanic tremor. Earthquakes associated with inflation and deflation of the Krafla central volcano were as large as M5. The largest earthquake caused by the Krafla rifting events did not occur in the Krafla volcanic system, but rather at the junction of the Krafla fissure swarm and the Tjörnes transform zone. This was an M6.5 strike-slip event (surface wave magnitude) on the Grimsey lineament within the Tjörnes transform zone where it links to the Krafla fissure swarm (often referred to as the Kópasker earthquake. It followed dike opening in the fissure swarm in preceding weeks which increased stress on the strike-slip fault (Einarsson, 1991).

Extensive opening of fractures and displacements on normal faults (up to several meters in individual events) occurred out in the Krafla fissure swarm, despite the fact that sizes of individual earthquakes there did not exceed M4.5.

Similar scenario could happen in the Kverkfjöll fissure swarm. Accumulation of magma at shallow depth in the Kverkfjöll central volcano would be expected prior to such magmatic rifting events. However, seismogenic difference between the Kárahnjúkar area and the Tjörnes transform zone should be emphasized.

Significant normal faulting earthquakes are also known to happen without association with magmatic activity. In June 1974 an earthquake of M5.5 occurred in the Borgarfjörður area (body wave magnitude). It was a part of an earthquake swarm preceded by increased seismic activity in the area in 1972-73. Earthquakes recorded by network of portable seismographs from June 28 – July 15, 1974 span depth range from 0 to 8 km (about the whole brittle crust) and obtained fault plane solutions indicating normal faulting (Einarsson, 1989; Einarsson *et al.*, 1977)

Aseismic slip can also occur on faults. The largest such known aseismic movement on a normal fault in Iceland occurred at the Almannagjá fault at Þingvellir, where a 9 cm subsidence occurred at the down-thrown block sometime between 1973 and 1977. Only small earthquakes accompanied this subsidence (Tryggvason, 1990). Aseismic movements therefore need to be considered as a possibility on faults in the Kárahnjúkar area.

The Kárahnjúkar area is at the flank of the spreading zone in North Iceland. Stress field in the area is influenced by extension across the plate boundary. This is supported by hydrofracture stress-measurements from geophysical borehole investigations at the Kárahnjúkar dam site (Amberg Measuring Technique, 1998). Activity along the central axis of the plate boundary in North Iceland may be compared to that on the Atlantic and Arctic ridges. Seismicity along the spreading part of the ridges (excluding transform faults) is dominated by small magnitude normal faulting earthquakes. However, examples of normal faulting earthquakes as large as M6.1 along the ridges are described by Einarsson (1987; *e.g.*, earthquake on the Arctic ridge in 1966 with m_b 6.1). It should be kept in mind that the Kárahnjúkar area is offset relative to the central axis of spreading in North Iceland, and earthquakes there may be somewhat larger than along the crest of the Mid-Atlantic Ridge. Along the Artic ridges, a recent example of a large normal faulting earthquake was an M6.2 earthquake that occurred on March 6, 2005 at 84.94°N, 99.14°E (National Earthquake Information Center, USGS).

6. Strike-slip faults at Kárahnjúkar

The nature of the fault array, including strike-slip faults, at and near the foundation of the main Kárahnjúkar dam is not well understood. Their mapped length is short, but experience from mapping of strike-slip faults in Iceland suggests that their surface expression is complex and often consisting of offset segments difficult to trace. Although there is no evidence for Holocene displacement on these faults, they are planes of weakness and have to be considered as candidate planes of triggered activity. The origin and nature of these faults requires a continued study, in particular because direct evidence for absence of activity on some of them throughout the Holocene period is currently lacking.

Helgason (2002) suggests that slickensides on fractures at the dam site relate to the Kárahnjúkar volcanic event. The Kárahnjúkar volcanic ridges roughly fall on line from Nónhnjúkar in the north to Sandfell in the south. Fractures with slickensides may originate from offset in the volcanism. However, there are indications for tectonic activity in the lowest part of sediments at Jökulsá overlying the fault array at Kárahnjúkar, suggesting tectonic activity in the area 150-250 thousand years ago (Guðmundsson, and Helgason, 2004)

The suggestion of close relation between geothermal activity and faults indicates high near surface permeability (Sæmundsson and Jóhannesson, 2005). Consequently the faults may be effective water pathways. In the seismic design report for the Kárahnjúkar project, it is pointed out that reservoir triggered earthquakes could potentially "open" some of the lineaments under Kárahnjúkar dam, contributing to reservoir leakage. Considering that excavation and further studies of the strike-slip faults in the area have revealed these to be more extensive than originally envisaged, this should be carefully considered. Furthermore, it should be kept in mind that fractures may open up without seismicity in response to increased water pressures, like the experience from Langalda implies (Tomasson, 1976).

Reservoir leakage is known at other hydroprojects in Iceland, but at Hrauneyjafoss and Sultartangi reservoirs it is < $6m^3/s$, and within limits predicted at the design stage (Freysteinsson and Helgason, 1986).

7. Potential future faulting and earthquakes in the Kárahnjúkar area

7.1. Stress fields and potential earthquakes

Future faulting and earthquakes in Kárahnjúkar area depend on prevailing crustal stresses in the area or stresses that may build up in the future from natural causes.. The increase in pore-pressure and load associated with the establishment of the Hálslón reservoir is only considered to act as potential trigger for activity that otherwise would occur at a later time. Absence of earthquakes in the Kárahnjúkar area in the last decades suggests stress levels somewhat below the breaking limit. The lack of earthquakes prevents use of seismological techniques for probing the direction of stress axis, but stress measurements in boreholes provide important constraints.

Geophysical borehole investigations were carried out in 1998 both at Kárahnjúkar and also at Teigsbjarg, by Amberg Measuring Technique (1998a and b). At Teigsbjarg, 13 hydrofracturing / hydrojacking tests were carried out in a single borehole between 155 and 412 m depth. The overburden stress, S_v, is the maximum principal stress, being larger than the horizontal stresses. The maximum horizontal stress, S_H, is directed NE-SW, and the minimum horizontal stress, S_h, is perpendicular to this. The stress regime is thus characterized by normal faulting stress regime ($S_h<S_H<S_v$). Furthermore, the measurements show that the minimum principal stress is low compared to hydrostatic pressure. Similar features of the stress field, although only observed in boreholes shallower than 200 m, were inferred at Kárahnjúkar. The inferred direction of the maximum horizontal stress is N31°±7°E at Teigsbjarg, and N28°±7°E at the Kárahnjúkar dam site. It is similar to the strike of the Sauðárdalur fault, suggesting current stress field in the area to be favorable for normal faulting earthquake on it, as well as on other planes striking NE-SW. This is a similar stress field to that found in the deeper levels of borehole at Reyðarfjörður in Eastern Iceland (Haimson and Rummel, 1982)

Potential failure of the Sauðárdalur normal fault along its complete length cannot be excluded. Normal faulting event on the fault would require a stress field with direction of minimum compressive stress perpendicular to the fault trace, as would be the case if strain associated with the spreading plate boundary would extend all the way out to this area. Currently, the central axis of plate spreading at this latitude is centered on the Askja volcanic system, but stress and strain associated with plate spreading movements may extend far away from the spreading axis.

Intraplate earthquakes larger than M5 are known to occur in and around Iceland. The most recent of these was the January 31, m_b 5.2 event off the eastern coast of Iceland. Another example is the previously mentioned 1974 earthquake swarm in Borgarfjörður. A review of intraplate earthquakes, epicentral distribution and possible causes is provided by Einarsson (1989).

7.2 Opening up of fractures by increased pore pressures

The geophysical borehole investigations (Amberg Measuring Technique, 1998a and b) show that minimum principal stress is low compared to the currently prevailing hydrostatic pressure, with their inferred difference being on the order of 1 MPa. The Hálslón reservoir with water depths exceeding 100 m over large areas and associated change in hydrostatic pressure over 1 MPa, may therefore modify the stress field so that hydrostatic water pressure will exceed the minimum principal stress, both at the site of Kárahnjúkar dam, but also along a considerable part of the Hálslón reservoir. Previously existing and open fractures in these areas may widen as a result, similarly to what happened at Langalda (see 3.1) in response to an order of magnitude smaller change in hydrostatic pressure. Tests of water conductivity at the Teigsbjarg site suggest irreversible change of hydraulic properties of the stimulated fractures during the injection (shearing of the stimulated fractures with an increase of fracture width).

The existence of low minimum horizontal stress close to hydrostatic has been known and considered in the dam design. The new geological observations (see chapter 4) including Holocene faulting under Hálslón, relation between geothermal activity and faulting, and extensive faulting under the Kárahnjúkar dam, do, however, all suggest fractures are more open and permeable than previously considered.

Actions to reduce the hazards associated with opening of fractures should be considered, including slow filling of the Hálslón reservoir at all stages.

7.3. Magmatic activity in nearby volcanic systems

Potential future movements on faults in the Kárahnjúkar area might be associated with magmatic activity in the Kverkfjöll volcanic system. In general, normal faults in the fissure swarm of Iceland are most likely to move in rifting events, in association with formation of dikes. Rifting events in the Krafla volcanic system 1975-1984 are the best available analogy for a potential future rifting event in the Kverkfjöll swarm. Accordingly, a rifting event may be associated with earthquakes with magnitudes up to M5 at Mt. Kverkfjöll, numerous earthquakes reaching up to M4 in the Kverkfjöll fissure swarm, and volcanic tremor. The earthquake activity would be associated with extensive fracturing and fault opening. Fault density in the Kverkfjöll fissure swarm is by far highest along the central axis of the fissure swarm west of river Kreppa, and that would be the most probable site of rifting. Dikes change the stress field over large areas, and can trigger fault movements far away from their traces. Movement on the Sauðárdalur fault could be induced by a rifting event at a considerable distance in the Kverkfjöll swarm. Judging from the inferred repeated movement on the Sauðárdalur fault, with potential several events occurring over 10.000 years, then the likely time between events is one in several thousand years. Similar triggered fault movement in the Kárahnjúkar area could be associated with magmatic activity in the Snæfell volcanic system, even if magmatic activity would not occur in the proper Kárahnjúkar area.

Magmatic movement in the adjacent volcanic systems could not only lead to normal slip on faults in the Kárahnjúkar area, strike-slip faulting could also be triggered, all depending on the pre-existing stress field and the stress fields generated by the magmatic activity.

The likelihood of the above mentioned scenarios can not be evaluated because of lack of knowledge about the behavior of the adjacent volcanic systems, but the repeat interval of such events is considered to be on the order of few hundreds or few thousand years.

Earthquakes in January 2005 in Vatnajökull provide a small example of interconnection of activity in nearby volcanic systems. An earthquake sequence in

Bárðarbunga totaling five events was detected January 25, with the largest one being a M2.5 event. One earthquake, smaller than M1.6, was then also detected at Kverkfjöll. Although Kverkfjöll is characterized by little activity, it could suddenly change, both by onset of inflow of new magma into its root, or by influence from other more active volcanic systems. In 1996, magmatic activity in Bárðarbunga preceded the Gjálp eruption. The scenario of events that preceded the Gjálp eruption began with seismicity in the same area as the January 2005 earthquake swarm.

7.4 Triggering of faulting in the Kárahnjúkar area by distant earthquakes

Dynamic triggering of slip on faults depends on the local stress field, the effective normal stress on faults, which keeps them clamped, and whether the amount of stress perturbation caused by the passing seismic waves can overcome the friction and induce slip. The small difference between minimum horizontal stress and hydrostatic stress in the Hálslón area suggests that slip on faults and opening of fractures might result from remote triggering, especially after the increase in pore pressure, caused by the reservoir, has lowered the effective normal stress on adjacent faults, bringing them closer to failure.

Results from Antonioli et al. (2005) show that variations in shear stress of up to ±0.1 MPa caused by the passing shear waves from the M6.5, June 17, 2000 earthquake, were enough to trigger two M~5 events at 65 and 77 km distance on Reykjanes Peninsula (Vogfjörd, 2003). The results require low effective normal stress, which as previously stated can be attained through high pore pressure. In fact, high pore pressure (close to lithostatic) at depths of a few km in the Hengill area was extracted from earthquake analysis by R. Slunga (personal communication, 2004), an area which also experienced a dynamically triggered M~3 event by the June 17 earthquake.

With faults in the Kárahnjúkar area weakened by increased pore pressure, the possibility of triggering of slip or opening, by stress perturbations brought by seismic waves from the closest earthquakes of M6.5-7, at 150 km distance in the Tjörnes Fracture Zone, becomes relevant.

8. Future tasks

This report is based on limited available information and thus considered preliminary as the following future work is recommended:

- A more extensive consideration of the topics addressed in this report.

- Analysis of the response of the Kárahnjúkar project's constructions to potential future earthquakes and faulting considering the new geological findings, including consideration of how stress and strain fields may interact with man-made structures.

- High-quality performance data and strong-motion records on and near dams are essential to better understand the behaviour of dams during earthquakes and to calibrate and improve methods of numerical analysis (see USCOLD, 1989; ICOLD, 1999).

• Considering the complex tectonic setting of the Kárahnjúkar area, and that the stress field in the area may be influenced by events in nearby areas, a greatly improved monitoring of earthquakes and crustal deformation is recommended in a wider area. Original monitoring plans considered only the immediate area surrounding Kárahnjúkar (Sigmundsson and Sigtryggsdóttir, 2004), but it is insufficient to fully understand the hazards in the area. The neighboring volcanic systems have to be taken into account, as well as the Vatnajökull ice cap. Bearing this in mind, we recommend a twofold purpose for a monitoring program of underlying hazards due to earthquakes and faults:

1. To determine any ongoing crustal movements and stress accumulation in the immediate Hálslón reservoir area.
2. To enhance understanding of possible mechanisms of stress accumulation and alteration in the Kárahnúkar area, such as loading by nearby volcanic systems, loading/unloading by mass changes of Vatnajökull, changes in regional pore pressure and Coulomb stress, induced by water level changes.

To achieve the goals of the recommended monitoring program, the following projects need to be considered:

i) Extend geological mapping and structural studies of faults in the wider Kárahnúkar area, including the fissure swarms of the volcanic systems Askja, Kverkfjöll and Snæfell.
ii) Extend monitoring of earthquake activity in Kárahnjúkar and adjacent areas, including nearby volcanic systems, Askja, Kverkfjöll and Snæfell. Better understanding of the seismic activity N and NE of Askja is of crucial importance because of a possible analogy with faulting in the Kárahnúkar reservoir area.
iii) Extend monitoring and measurements of crustal deformation and strain accumulation at Kárahnjúkar and adjacent areas. Of particular importance is to add more continuous GPS-stations, and also the establishment of a dense regional network of GPS-points to be re-measured at intervals of less than several years. The study area should include nearby volcanic systems and the Vatnajökull ice cap, with the regional GPS-network connecting to existing networks around Bárðarbunga and Krafla. Use of other geodetic techniques should be considered, including satellite radar interferometry and levelling.
iv) Detailed monitoring of displacements and creep on faults crossing the Hálslón reservoir and the dam sites.
v) Monitoring of pore pressure changes, both in the reservoir area and nearby fault systems.
vi) Theoretical studies and model calculations of stress loading and possible triggering of earthquakes and faulting events within the tectonic regime of Kárahnúkar.
vii) Theoretical finite-fault modelling of the potential scenario earthquakes and the resulting strong ground motions, with emphasis on quantitative estimates of directivity effects, and near-fault effects for earthquake engineering applications.

We like to emphasise that for a successful long-term monitoring and research program it is necessary to build up local expertise in the above fields. At the same time, we realize that the above suggested monitoring and research may have limited effect on the design of the Kárahnjúkar project.

9. Summary

i) The Kárahnjúkar area is currently considered seismically quiet. Recent geological investigations indicate, however, that Holocene faulting has occurred in Sauðárdalur extending under the future Hálslón, with last known fault movement occurring several thousand years ago. The fault system at the Kárahnjúkar dam site is also more extensive than previously considered, and the geothermal heat relates to faults in the area. These new observations suggest that the Kárahnjúkar area is not fully tectonically stable and geological hazards are more extensive than considered previously.

ii) Stress and strain fields in the area may change and revive seismic activity. The establishment of Hálslón and increased pore pressures may trigger faulting in the Kárahnjúkar area as well as enable remote triggering by distant earthquakes. Furthermore, faulting in the area may be triggered by magmatic activity in any of the nearby volcanic systems, including the Askja, Kverkfjöll, and Snæfell volcanic systems.

iii) The assessed maximum faulting event in the Kárahnjúkar area is estimated to be a normal faulting event with a seismic moment of $\approx 3\times10^{18}\,\mathrm{Nm}$, with a very long return period compared to earthquake activity in the main seismic zones of Iceland. The dimensions of the mapped extent of the Sauðárdalur fault are large enough to induce such an event. Cumulative moment in such a faulting event may be released in a series of earthquakes, partly by aseismic slip, or in a single earthquake. In any case, a significant normal faulting near-field earthquake should be given due consideration.

iv) Hazards from opening of fractures in response to increased pore pressure are considered significant as the minimum horizontal stress is low and close to hydrostatic, and series of fractures in the area can be expected to be highly permeable.

v) Expansion of a surveying program in the close vicinity of the dams and the Hálslón reservoir during the construction phases of the dams and filling of the reservoir is recommended, with the aim of measuring deformation and detecting potential openings of fractures in the reservoir and its vicinity due to increased loading and pore pressure.

vi) This report is based on relatively limited information and future tasks regarding hazards from earthquakes and faults should include continued consideration of the topics addressed herein, evaluation of response of planned structures to eventual hazards, and expansion of a monitoring and research program aiming at better understanding of the tectonic activity in adjacent volcanic systems. Activity in a broad area in North Iceland may influence hazards in the immediate vicinity of Kárahnjúkar. Although such a program may only have limited influence on the applied design provisions for the Kárahnúkar project, it will, on a longer time scale, reduce some of the uncertainties discussed in this report and facilitate response to, and mitigation of, future hazards.

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