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Geological challenges and geohazard monitoring of a mega engineering hydropower project in Iceland

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Geohazards must be considered, assessed and mitigated for all life-cycle phases of most mega infrastructure projects. This paper presents a unique mega engineering project, the 600 MW Kárahnjúkar Hydropower Project in Iceland. The construction site presented several interesting and complex geological and geophysical conditions, such as an unexpected discovery of an active fault in the foundation of the main dam (mega dam) and earthquake activity in a nearby volcanic zone caused by a subsurface volcanic intrusion during the first impoundment. The related apprehensions included predictions of: Persistent movements and opening of faults in the dam foundation causing excessive leakage, large reservoir induced crustal deformation that could trigger volcanic eruption or near field earthquake action such as reservoir triggered earthquakes that might affect the safety of the dam structures. The approach taken to resolve these apprehensions was to undertake specific investigations, assessments and monitoring, through a novel multidisciplinary organization. The focus of the paper is on describing the development and implementation of a holistic multi-source geohazard monitoring program for the main reservoir, Hálslón Reservoir and its dams. The discussion starts with a definition of what constitutes monitoring of geohazards within the framework of the project. This is followed by an outline of the monitoring networks implemented comprising instruments monitoring seismicity (micro-seismic stations and strong-motion instrumentation), crustal movements (continuous global positioning systems and benchmarks), fault movement (extensometers, joint and crack meters), groundwater elevation and leakage. Finally, a summary of key results from the geohazard monitoring is given. The geological challenges and related apprehensions are linked to the relevant research and investigations carried out, the monitoring networks installed, and the results produced, which demonstrate that during and after the first impoundment the key monitored processes were all within the pre-set limits. The case presented is relevant for current and future mega engineering projects as it demonstrates that a monitoring program set up to guard operational safety in the spirit of potential failure mode analysis, will provide important information on geo-environmental impact of a mega engineering project, not only for scientific interest but also for public information.

1. Introduction

In planning and implementing a hydropower project involving reservoir impounding, geohazards must be considered, assessed and mitigated for all the project's life-cycle phases. Herein geohazards in a hydropower project perspective follow the classification of Sigtryggsdóttir et al. (2015) and refer to hazardous events arising from geological, as well as hydrological conditions, both local and regional. The presence of criticalities in a reservoir's dam foundation such as faults are an example of local geohazard, while regional geohazards include for example earthquakes and volcanism. The danger arising from geohazards poses a threat to the safety of a reservoir and its dams. This is evident from the numerous incidents reported on in the literature (Lin et al., 2014; Wieland, 2009; Stapledon, 1976; Nonveiller,

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1987). Additionally, one geohazard may trigger or be interrelated to another (Sigtryggsdóttir et al., 2016; Wei et al., 2018). Furthermore, the impounding and operation of a reservoir may contribute to the triggering of geohazard related events, e.g. reservoir triggered earthquakes (RTE) (Lomnitz, 1974; Lane, 1974; Meade, 1991; ICOLD (International Commission on Large Dams), 2011; Rajendran et al., 2013) and landslides (Schuster, 1979; Wang et al., 2005; Qi et al., 2006; Song et al., 2018) that further may induce impulse wave on the reservoir (Ibañez and Hatzor, 2018). The potential hazardous consequences of such geohazard triggering are intensified in the case of a mega dam retaining the reservoir.

Monitoring of important geological features comprising a possible geohazard or relevant processes is thus of vital importance in guarding overall safety and reliability of a reservoir and its dams. In addition, monitoring of one geohazard may provide information on the development of another (Sigtryggsdóttir et al., 2016). The literature includes reports on monitoring programs in conjunction with actual reservoirs and dams that mainly focus on observing one or two specific geohazards. This includes: the seismic monitoring in relation with RTE's of the Koyna and Warna reservoir site in India (Gupta and Combs, 1976; Yadav et al., 2013) as well as near the Osmansagar reservoir (Rastogi et al., 1986); seismic monitoring and groundwater measurements in relation to the seismicity of the Koyna region (Gupta, 2001); monitoring of crustal movements and seismicity (Abdel-Monem et al., 2012) in the Aswan region (Lake Nasser), Egypt; monitoring of an ancient landslide reactivated by the impounding of the Geheyan reservoir, China (Qi et al., 2006), and the monitoring of a landslide in the Aosta Valley, Italy, impinging on a concrete arch gravity dam (Barla et al., 2010).

However, it is difficult to find in the literature a case study that reports on the development and implementation of a multi-disciplinary organization of a holistic geohazard monitoring program for reservoirs and dams. In this paper such an account will be given on the case of the Hálslón Reservoir in Iceland. The importance of such schemes for overall reservoir and dam safety is demonstrated for the general case by Sigtryggsdóttir et al. (2016) in a quantitative analysis of interrelations in a multi-source geohazard monitoring using a conceptual model (Sigtryggsdóttir and Snæbjörnsson, 2019).

The objective of this paper is to give a holistic account of the challenges encountered related to geohazards in the Hálslon region and how they were evaluated and resolved through investigations, assessment and monitoring using an organized multidisciplinary approach.

The paper presents the geohazard investigation, assessment and monitoring for the Hálslón Reservoir of 2100 million m^3 and 57 km^2, the main storage for the 690 MW Kárahnjúkar Hydropower Project (KHP) in Iceland (Figs. 1 and 2a). The construction of the KHP was initiated in 2003. Impounding of the reservoir started late September 2006, and the full supply level (FSL) was reached in October 2007 (Fig. 2b).

The Hálslón Reservoir drainage basin is 1800 km^2, of which 1400 km^2 are covered by Iceland's (and Europe's) largest glacier, Vatnajökull. The inflow into the reservoir is therefore dominated by the annual glacial meltwater discharge. The reservoir extends 25 km north from the glacier area to Mount Kárahnjúkur, where it is retained by three dams (Fig. 2). The largest dam is the Kárahnjúkar Dam (K Dam), a 198 m high concrete faced rockfill dam (CFRD), built across a narrow and deep canyon with up to 90 m high canyon walls. A grouting inspection gallery is provided in the foundation of this dam with tunnels on each side of the canyon, interconnected with a passage through a concreted toewall at the bottom of the canyon. The two saddled dams, Desjarár Dam (D Dam) and Sauðárdalur Dam (S Dam), are respectively 70 and 25 m high. These are both earth-rockfill dams with a central core of moraine. A spillway is provided at the northwest bank of the K Dam and a fuse plug at the southeast end of the D Dam (Fig. 2). The S Dam is founded on layers of sediments. The foundation of the D Dam and K Dam is described in the following, along with the geological settings of the reservoir site.

There are many aspects of this mega engineering project that makes it interesting and worth reporting, all relating to complex geological and geophysical conditions, including the unexpected discovery of an active fault in the foundation of the K-Dam and earthquake clusters recorded in a nearby active volcanic zone during a subsurface volcanic intrusion. These complications crystalize in concerns expressed by geoscientists regarding the KHP in relation to geohazards. Both apprehensions prior to construction that the reservoir might trigger volcanic eruption, as well as speculations during the reservoir impounding on whether the earthquake clusters that were recorded indicating subsurface magma movement might have been triggered by the impounding. As the authors have not found similar speculations on potential triggering of volcanism due to reservoir impounding in the literature, they feel obligated to report on this.

In this paper the tectonic and geological setting of the area are

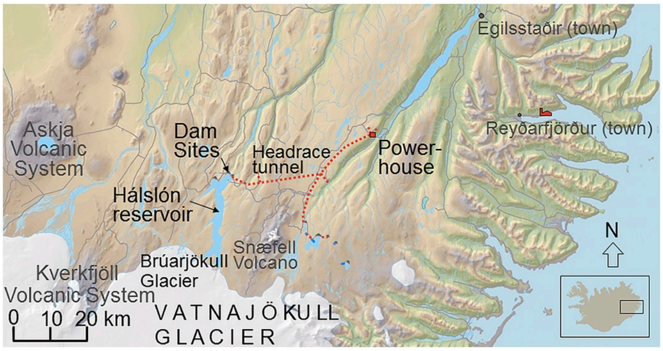


Fig. 1. Location of the Kárahnjúkar Hydropower Plant and the Hálslón reservoir.

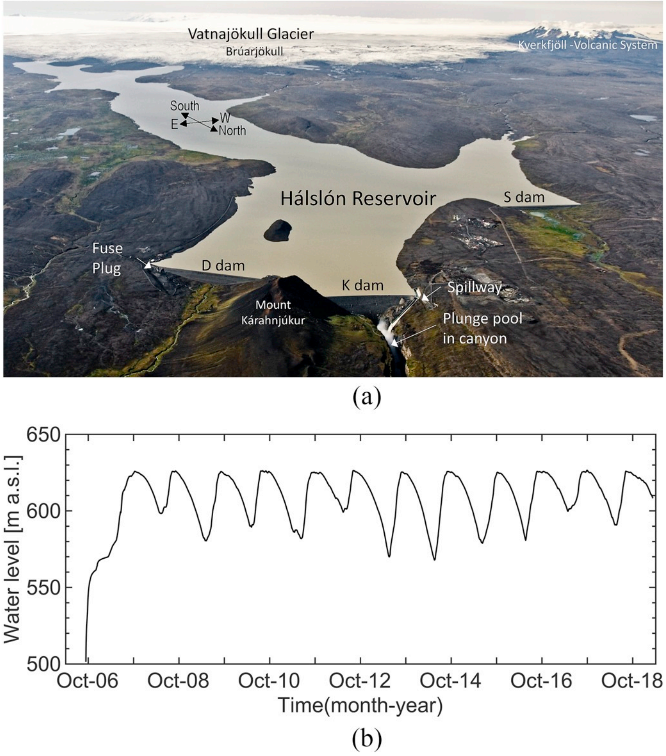


Fig. 2. The reservoir: (a) Hálslón reservoir and dams, with water on the spillway. The reservoir is 25 km long. Length of the three dams at crest elevation is 730 m for the K Dam and 1100 m for both the D and S Dam. (Photo courtesy of Emil Thor). (b) Reservoir water level in m above sea level since the start of impounding until March 2019.

Table 1
Geological challenges and/or apprehensions relating to geohazards.

Nr	Challenges/apprehensions
A1	Reservoir triggered earthquakes
A2	Excessive leakage
A3	Crustal deformations due to the reservoir may trigger volcanic eruption
A4	Reservoir induced settlements (in meters)
A5	Persistent movements on faults in the dam foundation
A6	Opening of faults in the reservoir and dam foundation
A7	Near field earthquake action of concern for dam structures

outlined so that the challenges and concerns expressed on geohazards can be comprehended. Geological investigations and geohazard assessment are described and apprehensions relating to geohazards are discussed and listed (Table 1). These concerns were widely used in the public debate to discredit the KHP. Definition is given of what constitutes monitoring of geohazards, followed by an outline of the monitoring networks implemented for the KHP. Furthermore, an important multidisciplinary approach to the impounding organization is described, involving a group of specialists reviewing the monitoring information. Finally, a summary of results from the geohazard monitoring is given for the period of multidisciplinary review of the monitoring data spanning the impounding period and couple of years of reservoir operation. Results after this period is also reported when relevant for the apprehensions listed. At every stage the apprehensions listed in Table 1 are linked to the relevant topic, such as research and investigations carried out, the monitoring networks, and finally the results.

The multidisciplinary approach described herein has elements related to some of the steps of a potential failure mode analysis (PFMA). Hariri-Ardebili et al. (2016) provide e.g. an example of seismic PFMA for concrete dams. The concept of PFMA for risk analysis and dam safety monitoring is respectively described e.g. by USBR and USACE (2015) and FERC (2017), considering mainly existing dams. USBR and USACE (2015) explain that a prerequisite for such analysis is a thorough compilation of all relevant background information by all members of the team involved. In particular, the interaction of disciplines is emphasized, as this may reveal vulnerabilities that would otherwise be missed. FERC (2017) describes how the results of a PFMA can be utilized for a more effective development of surveillance and monitoring plans, as implemented in the approach described here. However, in addition to considering dam safety directly, the geophysical and geoenvironmental impact was also of concern for the current case. Furthermore, the apprehensions of third parties were deliberated. Moreover, the multidisciplinary approach discussed demonstrates the value of a PFMA related methodology, not only for existing dams, but also during planning and construction of a new mega dam including observations during the first filling of the reservoir.

Hence, the novelty and significance of the paper lies in the methodology presented on the development and implementation of a multidisciplinary organization of a holistic geohazard monitoring in a Mega Engineering Project (MEP). A comparable multidisciplinary approach to geohazard monitoring of hazardous infrastructure is difficult to find in the literature. Hence, reporting on the challenges and settings instigating this multidisciplinary geohazard review, as well as on the organization of the process and successful outcome is important and of interest for future infrastructure projects and demonstrates the relevance of engineering geology for MEPs.

The purpose of the paper is to promote this important methodology that relies largely on investigations, analysis and conclusions from engineering geologists. The emphasis is to provide an overview of the challenges and how these where tackled through first, investigations, research and analysis providing means to define design/safety limits, and then monitoring of relevant processes for early warning of potential undesirable trends. Details of the analysis conducted for each process are not the topic of this paper, but key results relevant for answering the listed apprehension are presented.

2. Challenges relating to geohazards

The main geohazard related challenges for the dam design were the complex geophysical and geological conditions in the larger reservoir area along with discovery of unknown faults in the dam foundations during the construction phase. An overview of the geophysical and geological setting is given in this section, in order to explain the background for the concerns expressed regarding potential geohazards during the preparation and construction phases of the project.

2.1. Geophysical and geological setting

Iceland is a volcanic island (Thordarson and Larsen, 2007) straddling the Mid-Atlantic Ridge which marks the boundary of the North-American Plate and the Eurasian Plate. These plates are continuously moving apart, resulting in continual intrusion of magma on the boundary which again leads to tectonic activity. The main volcanic zones of Iceland (Jóhannesson and Sæmundsson, 1998) (Fig. 3a) follow the Mid-Atlantic Ridge. These are also referred to as spreading zones. The spreading of the plate boundary in Iceland is little < 2 cm/yr (Geirsson et al., 2006, 2010), this can be viewed as the North-American Plate moving about 1 cm/yr to the north west while the Eurasian Plate moves 1 cm/yr to the north east (Fig. 3a) (Sigbjörnsson et al., 2018).

The Icelandic crust is relatively thin (10–46 km) (Allen, 2002) and north of the Vatnajökull glacier the crust is around 10–15 km (Björnsson, 2008). Post-glacial rebound uplift due to the melting of Vatnajökull is in the range of 12 mm/yr in the vicinity of the glacier. In central Iceland the uplift rates are about 25 mm/yr partly attributed to glacial isostatic adjustment (Völksen et al., 2009). Deformations close to Vatnajökull ice cap have a peak-to-peak seasonal displacement of ~16 mm (Grapenthin et al., 2006).

Hálslón and its dams are located outside the main seismic hazard zones of Iceland, but close to the south east margin of the Northern Volcanic Zone (NVZ), as shown in Fig. 3. The latest eruptions in the area east of this margin, including the dam sites, have occurred during the second last glaciation ~200 kyr ago. The foundations of the K and D Dams comprises various geological units (Fig. 4), including layers of basalt lava flows of different origin formed in eruptions during interglacial eras. The foundation is transected by numerous faults, lineaments and fissures which will be described in more detail in the following. The most pronounced fault in the foundation of the 198 m high K Dam (labelled DF-1 in Figs. 4 and 5) was encountered during excavation in the construction phase. The fault was defined active and is located where the water pressure due to the reservoir is at its highest. The geology at the dam sites is described in more detail in Section 3.

The main volcanic systems in the NVZ are shown on Fig. 3b. The volcanos Kverkfjöll and Askja are closest to the dam site. Also close, but outside the NVZ, is the currently inactive Snæfell Volcano (i.e. with no verified eruption of Holocene age). The Kverkfjöll volcano laterally feeds the eruption of fissures in the south-easternmost part of the NVZ, called the Kverkfjöll fissure swarm. The volcanic systems and fissure swarms in Iceland are further explained by Thordarson and Larsen (2007) and Hjartardóttir et al. (2016).

Five volcanic systems have been identified under the Vatnajökull ice cap, each containing central volcanoes and fissure swarms. The most active are the volcanic systems Grímsvötn and Bárðarbunga (see Fig. 3b). A volcanic eruption under the Vatnajökull glacier triggering glacial outburst flooding into the Hálslón Reservoir is a potential catastrophic event for the Hálslón Reservoir and its dams. The ice and water drainage basins of the glacier were delineated, and the location and geometry of subglacial lakes identified (Björnsson, 2003). It was found that, assuming the meltwater from a subglacial eruption site will continue to drain through existing conduits, the catchment area of the

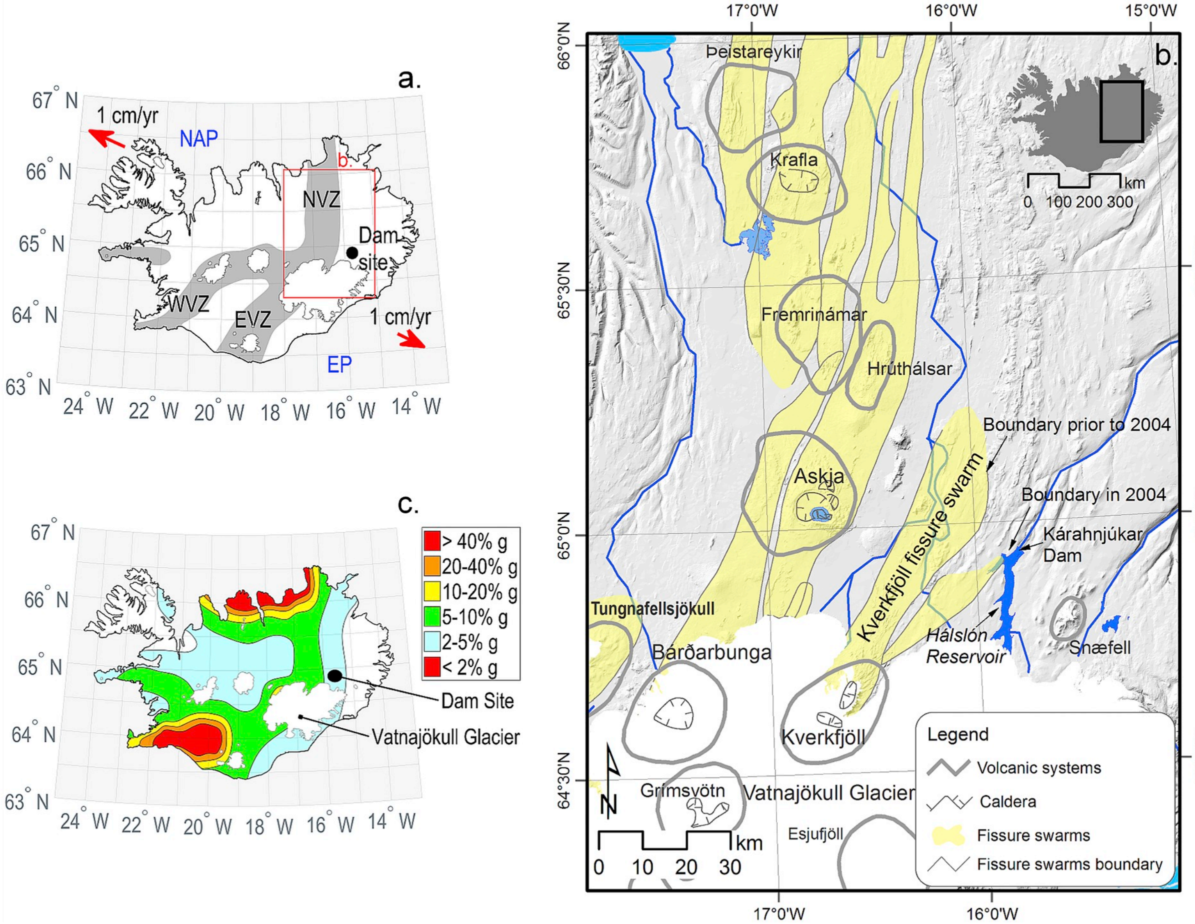


Fig. 3. Tectonic settings of Iceland. (a) Volcanic spreading zones (grey area). (NVZ, WVZ and EVZ refer respectively to the North-, West- and East- Volcanic Zones; NAP and EP refer respectively to the North American and Eurasian Plates). (b) Volcanic systems within the Northern Volcanic Zone (NVZ). The boundary of the Kverkfjöll fissure swarm is shown as defined prior to and after the 2004 re-evaluation. (Location of fissure swarms: Hjartardóttir et al. (2016), tectonics: Jóhannesson and Sæmundsson (1998), and volcanic systems: from a map from 1987 by Einarsson and Sæmundsson). (c) An earthquake hazard map showing isocontours of horizontal PGA with a mean return period of 475 years (adapted from Sólnes et al., 2004).

reservoir will most likely not be affected. During the design phase of the project, glacial outburst flood into the reservoir was thus considered theoretically possible event, but improbable. However, favoring dam safety, a fuse plug was provided at the east end of the D Dam to be used in case of such extreme event.

The earthquakes originating on the spreading zones are relatively small, with magnitudes that seldom exceed five (Einarsson, 1991 and 2008). The largest earthquakes occur at transform faults and fracture zones in South and North Iceland (Einarsson, 2008; Wolfe et al., 1997). This is evident when relating the maps on Fig. 3a and c. The hazard map on Fig. 3c indicates that the dam site is located in a low hazard area with peak ground acceleration (PGA) of only 0.02–0.05 g for a mean return period of 475 years. Still, the design criteria defined considerably higher PGA as explained in Section 3.

2.2. Apprehensions relating to geohazards

The challenges inherent in the geophysical and geological settings in the larger reservoir area gave rise for concerns regarding the safety of the dams holding the reservoir. Apprehensions relating to geohazards were expressed both prior to and during construction of the dams, as well as during impounding of the reservoir. The key concerns raised are listed in Table 1 and discussed in this section.

Following an environmental impact assessment issued in 2001, concerns were expressed by geoscientists and parties opposing the project due to its environmental impact, regarding potential geohazard related risks in the Kárahnjúkar area (referred to also as the Hálslón Reservoir area after the impounding). In spite of the decision by the Ministry for the Environment and Natural Resources to authorize the project. Among the apprehensions was that the bedrock in the Kárahnjúkar area was not well suited as a dam base considering the fractured characteristics of the crust, indicating unsafe foundation prone to excessive leakage. Moreover, that crustal deformation due to fluctuations in the glacial loading and unloading of Vatnajökull Glacier might cause repeated movements on faults in the dam foundations. A question was raised whether this in combination with annual cycles in the reservoir water level could potentially trigger earthquakes (RTE) and/or affect magma flow and volcanism in the region. It was for instance stated that the reservoir might induce ground settlement measured in meters.

The debate was intensified by the fact that during the construction phase, active faults were encountered in the foundations of the K and D Dam (Figs. 5 and 6). Only a month prior to the reservoir impoundment concerns regarding the safety of the dams were highlighted in public debate. This included apprehension concerning potential excessive leakage and large movements on faults in the dam foundation induced by water pressure from the reservoir. For instance, a question was raised regarding how much the fault (DF-1) underneath the K Dam would open after the impounding. The question was illustrated with a schematic figure, adopted in Fig. 7.

During the reservoir impounding an episode of earthquake activity started within the Kverkfjöll fissure swarm in the Northern Volcanic

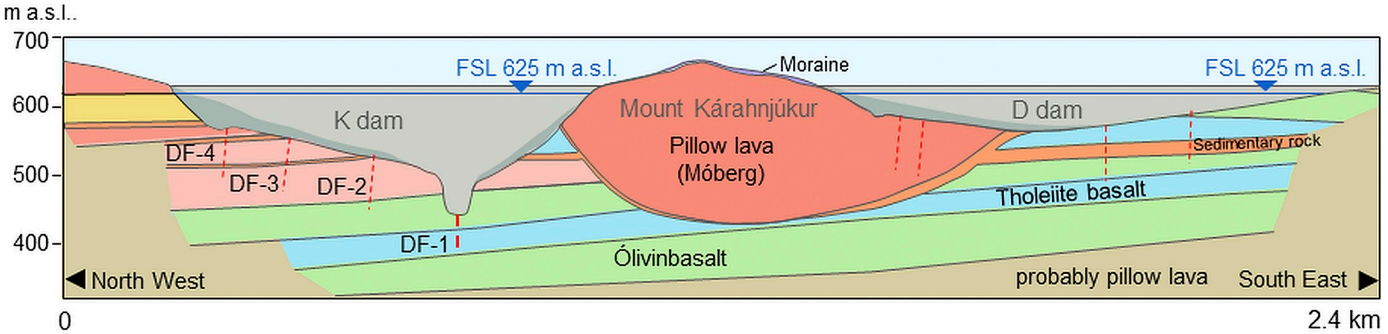


Fig. 4. Geological section through the ridge Mount Kárahnjúkur at the site of the Kárahnjúkar (K) and Desjarár (D) Dams (see Fig. 5 for dam location). The dashed red lines represent the approximate location of the main faults encountered in the foundation of the K Dam during the construction phase. In the foundation of the K Dam the faults are labelled DF-1 to DF-4. (Based on Gudmundsson and Helgason (2004)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

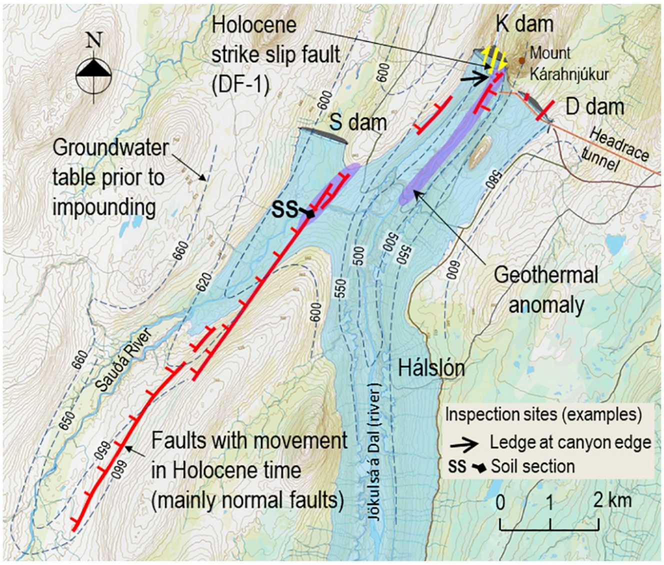


Fig. 5. The dam site and the reservoir, along with groundwater contour lines prior to inundation and Holocene faults identified during the construction phase. The inspection sites pointed out here are further shown in Fig. 8. (Based on a map made by Landsvirkjun and Iceland GeoSurvey).

Fig. 6. The canyon to be crossed by the K Dam. Excavation of the foundation revealed the Toe-wall Fault (DF-1), later defined as Holocene strike slip fault (see also Figs. 5 and 8a). (a) View towards upstream (south), the arrow points to location of Fig. 6b. (b) View towards downstream (north), the fault is trending 20–25° NNE and considered to be a right-lateral strike slip fault.

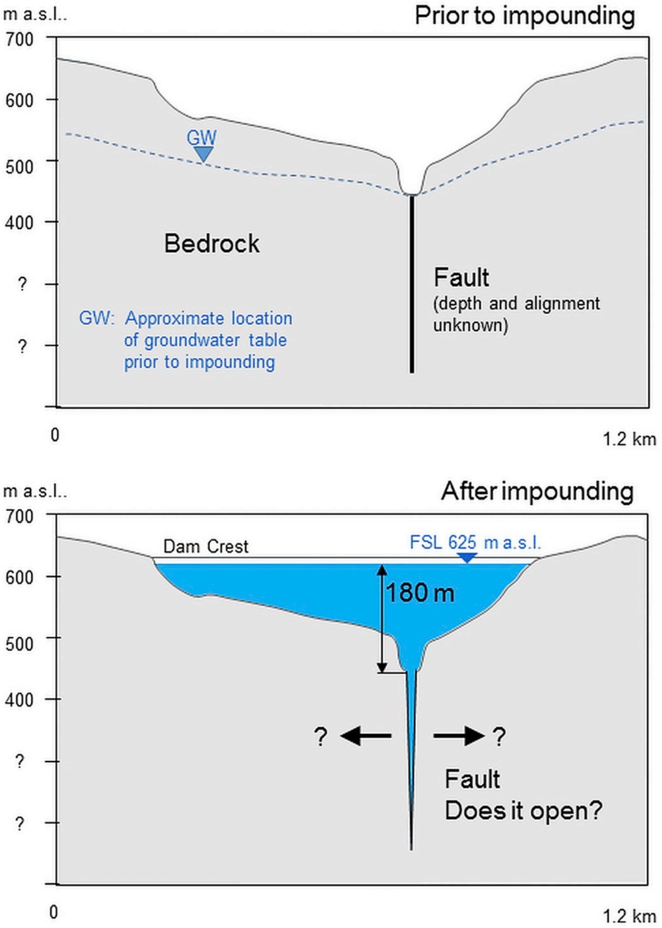


Fig. 7. Question on the behaviour of the Toe-wall Fault (DF-1) (see Figs. 5 and 6) in the foundation of the K Dam during impoundment.

Zone (NVZ). The largest earthquakes were of magnitude 2.3. More than 9000 tremors were recorded as a part of this activity from February 2007 to April 2008 (Jakobsdóttir et al., 2008). It was stated by geophysicists that this episode could potentially be related to the Hálslón Reservoir impounding and might eventually result in a volcanic eruption. The potential relations of this micro seismicity to the impounding of the reservoir were therefore deliberated during the impounding period.

There were different opinions regarding the viability of the above apprehensions (see Table 1) which were widely used to discredit the KHP. However, in the interest of dam safety the relevance's of these complications were duly considered by the owner, Landsvirkjun (The National Power Company of Iceland), and investigated. The implemented investigations and research on geohazards are outlined in the next sections, along with a description of the monitoring scheme and presentation of key results.

3. Investigations and research on geohazard

Geological investigations of faults and lineaments and ensuing evaluation of past fault displacements are required to identify and characterize potential geohazards. The geological findings are essential for the assessment of seismic hazard, rock fault behavior, groundwater regime, leakage and more. Furthermore, these aspects need to be considered when planning a comprehensive monitoring of geohazards. This chapter introduces how these features were studied for the Kárahnjúkar Hydropower Project (KHP) since early on in the reconnaissance phase and describes how new geological findings led to the reevaluation of geohazards and introduction of an associated monitoring scheme. Investigations carried out during the progress of the project are summarized in Table 2. The data and information gathered also provided material in to response to the apprehensions listed in Table 1.

3.1. *Reconnaissance and pre-construction phases*

Geological investigations for the project were originally initiated in the late 1970's, followed by more detailed investigations in the dam area in the 1990's (Stefánsson and Kröyer, 2008), along with a seismic hazard assessment. Geological Investigations on faults and fractures at and around the dam sites were conducted on several occasions during the pre-construction phase. These were somewhat constrained by thick overburden and difficult site conditions in the canyon to be crossed by the K Dam. Furthermore, before the construction was approved official environmental regulations limited the allowable geological studies at the site, to core drilling and digging of investigative trenches. The early mapping and study of fissures were thus mostly based on careful logging on exposed rock, core drillings and a 50 m long exploratory tunnel that was constructed at the left abutment of the K Dam. Consequently, necessary geological investigations extended into the construction phase.

Geological investigations during the pre-construction phase did not reveal any movement in Holocene time on the faults encountered in the dam area and thus no faults were defined as active. Nevertheless, the possibility of active faults in the dam area was considered in the original seismic design criteria for the dams. The pre-construction assessment of earthquake action defined a Maximum Credible Earthquake (MCE) with a PGA of 0.26 g and a potential near-field RTE of short duration with a PGA of 0.5 g (Sigtryggsdóttir et al., 2012).

Additionally, in response to apprehensions A4 and A3, listed in Table 1, the effect of the reservoir on crustal movements was studied by Sigmundsson (2002) resulting in an estimated maximum subsidence of ~30 cm, assuming a crust thickness of 10 km. It was reasoned that this was unlikely to induce magma movements under the crust, since there were no known indications of the existence of magma in the upper crustal layers.

3.2. *Construction phase*

During the excavation of the foundation of the Kárahnjúkar (K) and Desjarár (D) Dams a complex fault system was encountered (Gudmundsson and Helgason, 2004) (see Figs. 4, 5, 6 and 8) . Of special concern was a fault encountered in the foundation of the K Dam (Figs. 5, 6 and 7), which was judged to be of strike-slip nature. This fault, trending N20–22°E, labelled DF-1 is also referred to as the Toe-wall Fault and has been considered particularly important due its location in the canyon directly under the K Dam (see Figs. 4, 5, 6 and 7). Fig. 8a shows the Toe-wall Fault, DF-1, as it crosses a ledge west of the

Table 2
Investigations related to geological challenges and/or apprehensions listed in Table 1.

Challenge/apprehension		Investigations, before and after new geological findings
A1	Reservoir triggered earthquakes	Reservoir triggered earthquake considered in seismic analysis of dams with an earthquake time series of short duration and a PGA of 0.5 g.
A2	Excessive leakage	Geological investigations, tracing of leakage paths through faults, groundwater models, leakage assessments. A numerical model developed by Kárahnjúkar Engineering Joint Venture (KEJV) for simulating leakage, was revised to incorporate the latest geological findings and predictions of fault movements. The results indicated a total leakage of 5 m^3/s considering grouting measures in the dam foundation. (see also for A6).
A3	Crustal deformations due to the reservoir may trigger volcanic eruption	Based on a study by Sigmundsson (2002), on crustal deformation due to the reservoir loading, it was reasoned that this was unlikely to induce magma movements under the crust, since there were no known indications of the existence of magma in the upper layers.
A4	Reservoir induced settlements (in meters)	The crustal settlement due to the reservoir impoundment was estimated assuming e.g. a crust thickness of 10 km, resulting in an estimated maximum subsidence of ~30 cm (Sigmundsson, 2002).
A5	Persistent movements on faults in the dam foundation	A numerical study on the rock fault system under the K- and D-Dams was conducted using a finite difference model to quantify the quasi-static crustal movements beneath the Dam area related to the reservoir impounding. The goal was to estimate possible openings of faults due to pore pressure induced by the impounding. It was found that the tectonic movements would only be of the order of 3 cm, and therefore insignificant compared to the previously estimated seasonal cyclic crustal settlement due to reservoir impounding. The overall conclusion was that it should be sufficient for design purposes to allow for a 10 cm differential displacement on faults (Snæbjörnsson et al., 2006) and (Snæbjörnsson et al., 2006b) These findings were incorporated into the design criteria for the dams. Study by KEJV on possible leakage caused by an open fault in the K Dam foundation indicated an increase in total leakage of 0.15–1.5 m^3/s depending on the permeability (k = 0.1–1.0 m/s).
A6	Opening of faults in the reservoir and dam foundation	
A7	Near field earthquake action of concern for dam structures	The review on earthquake hazard and resulting action in the Hálslón area focused on near-field events, considering the latest information on faults and overall relevant geology. Credible earthquake scenarios were defined assuming earthquakes originating on the normal Sauðárdalur-fault and the strike-slip fault in the K Dam foundation. The predicted maximum PGA for the simulated motion was 0.30 g (Snæbjörnsson et al., 2006a) compared to the 0.26 g in the design criteria prepared during the pre-construction phase.

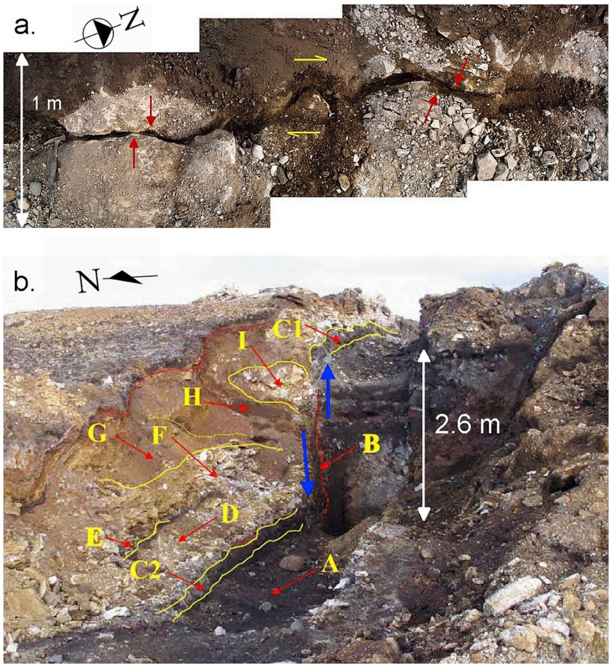


Fig. 8. Inspection sites in Fig. 5 (arrow and label SS): (a) Holocene strike slip fault (DF-1, the Toe-wall Fault) on a ledge west of the Jökulsá River, south of the K Dam. (See arrow to inspection site in Fig. 5). The fault trends N20–22°E. (Figure courtesy of Kristján Sæmundsson). (b) Holocene fault. Cross section striking approximately N120°E. Fault displacement relative to tephra marker C is 2.6 m. (For location see inspection site SS on Fig. 5) (A: Tillite or moraine, presumably some 10.000 yr. age; B: Fault escarpment, striking N29°E, showing a downthrow direction; C1, C2. E: Black tephra; D, F, G and I: Different silica deposits; H: Hard soil with prehistoric tephra layers). (Figure courtesy of Ágúst Guðmundsson).

canyon, south of the K Dam (for location see the arrow pointing to the ledge on Fig. 5). Sæmundsson and Jóhannesson (2005) inspected the fault and concluded that a right lateral slip of about 10 cm could possibly be observed on the fault. Furthermore, that uncemented fill of 3 cm could be taken as representing the amount of possible Holocene movement.

In the summer of 2004, an escarpment east of Sauðá River (Fig. 5), termed the Sauðárdalur Fault, was encountered in conjunction with an investigation on geothermal activity in the reservoir area. This fault was further investigated and found to be a normal fault with a throw of about 2.6 m in Holocene time (Gudmundsson and Helgason, 2004). The throw can be recognized from the soil section in Fig. 8b, which location is marked and labelled SS in Fig. 5. The earliest recognizable Holocene movement on this fault, occurred about 9000 years ago and the latest around 5000 years ago (Sæmundsson and Jóhannesson, 2005). The length of this fault is 14 km and it is visible as far north as Sauðá River.

New geological findings by Sæmundsson and Jóhannesson (2005) included a suggestion that this escarpment at Sauðá was an extremity fault linked to the Kverkfjöll fissure swarm. It was tentatively concluded that lava last erupted from the Kverkfjöll fissure swarm about 900 years ago most likely accompanied by activation of faults and ground fissures which were limited to the central part of the Kverkfjöll fissure swarm. It was further found that movements on faults, apparently connected to the formation of this lava did not extend to the easternmost part of the Kverkfjöll swarm and thus the dam sites. However, an evidence was found in the dam area for a volcanic episode in Kverkfjöll some 5–6000 year ago, which coincides in time with the last fault movement in the area as well as with the end of sinter deposition. These findings by Sæmundsson and Jóhannesson (2005) brought clearer forth the hazard potential of the Kverkfjöll Volcano and fissure swarm for the reservoir, by redefining the south-easternmost margin of the Northern Volcanic Zone (NVZ) further to the east, i.e. closer to the dam sites as shown on Fig. 3b, which depicts the expected boundaries of the Kverkfjöll fissure swarm prior to and after the 2004 findings.

A review of geohazards for the Kárahjúkar Hydropower Project was instigated in early 2005 following the new geological findings in 2004. The review was conducted by seven specialists on geophysics, seismology and earthquake engineering. The resulting report (Sigmundsson et al., 2005) presented a brief qualitative review of potential hazard with limited quantitative assessment of the likelihood of the different scenarios outlined. Recommendation were however presented regarding future research and extended monitoring tasks. Research and monitoring tasks, in line with the recommendations, were in some cases already ongoing while others were instigated following the review. Table 3 provides a summary of the research and monitoring tasks and relates those to the apprehensions listed in Table 1. However, monitoring alone was found to provide concrete answers to many of the questions debated at the time. This will be discussed in the next section.

4. Monitoring of geohazards

A geohazard monitoring scheme is of importance for guiding overall safety and reliability of reservoirs and dams, especially in the case of a mega dam. Such a scheme should include detection of the general effects of a reservoir on the geoenvironment. Thus, when developing a pertinent monitoring scheme, base or reference conditions for the geoenvironment need to be established by initiating the monitoring some years prior to construction or reservoir impounding.

The monitoring scheme for the Hálslón Reservoir and Dams was partly installed during construction but restructured following the geohazard review by Sigmundsson et al. (2005). The resulting geohazard monitoring scheme is outlined in Fig. 9, and was defined to include monitoring of seismic activity, crustal and fault movements, leakage and groundwater levels.

When restructuring the geohazard monitoring, it was recognized that it should embrace multiple interrelated sources requiring a transparent and organized multidisciplinary approach. To account for this, a group of earth scientists and engineers was formed to oversee the monitoring. In this section the organization of the geohazard monitoring scheme is described, including the definition of base conditions and contribution of the multidisciplinary task force.

4.1. Networks and instrumentation

Instrumentation installed in the Hálslón area aims to monitor changes in the environment related to geological conditions, which constitutes monitoring processes related to the geohazards summarized in Fig. 9. The various monitoring networks and instrumentation were installed and operated by different institutions by request from the owner of the Kárahnjúkar Hydropower Project (KHP). The monitoring networks installed are outlined in (i) to (vi) below:

(i) A network of micro seismic stations (Fig. 10) was installed to monitor seismic activity in the reservoir area as well as in the nearby volcanic systems, especially the Kverkfjöll Volcano. Furthermore, to identify from micro seismic activity, potential faults in the reservoir foundation and thereby potential pathways for leakage.

(ii) Strong motion instrumentation was installed on and near the dams (see Fig. 11) to monitor their behaviour in the case of an earthquake. The standard setup for the dams included a tri-axial accelerometer at the dam crest to monitor structural response and another in or close to the dam foundations to monitor the incoming ground motion. The data collected during any observed events can be used for calibration of numerical structural models as well as to validate and possibly refine the seismic design of the project.

(iii) For monitoring crustal movements and deformations (Fig. 12),

Table 3
Monitoring scheme linked to the apprehensions listed in Table 1.

Network/instrumentation	Monitoring	Providing information for apprehension A#
Micro-seismic monitoring stations in the immediate and larger reservoir area	A1	A1, A2, A3, A7
Ground motion and response monitoring systems, on or near the Dams	A7	A1, A3, A7
GPS monitoring of crustal movements on the surface in the immediate and larger reservoir area	A3, A4	A1, A2, A3, A4, A5, A6, A7
Joint meters and/or crack meters monitoring of faults in the Dam foundation	A5, A6	A2, A5, A6
Groundwater elevation in the immediate and larger reservoir area		A1, A2, A6
Leakage observations downstream of the Dams	A2	A2, A6

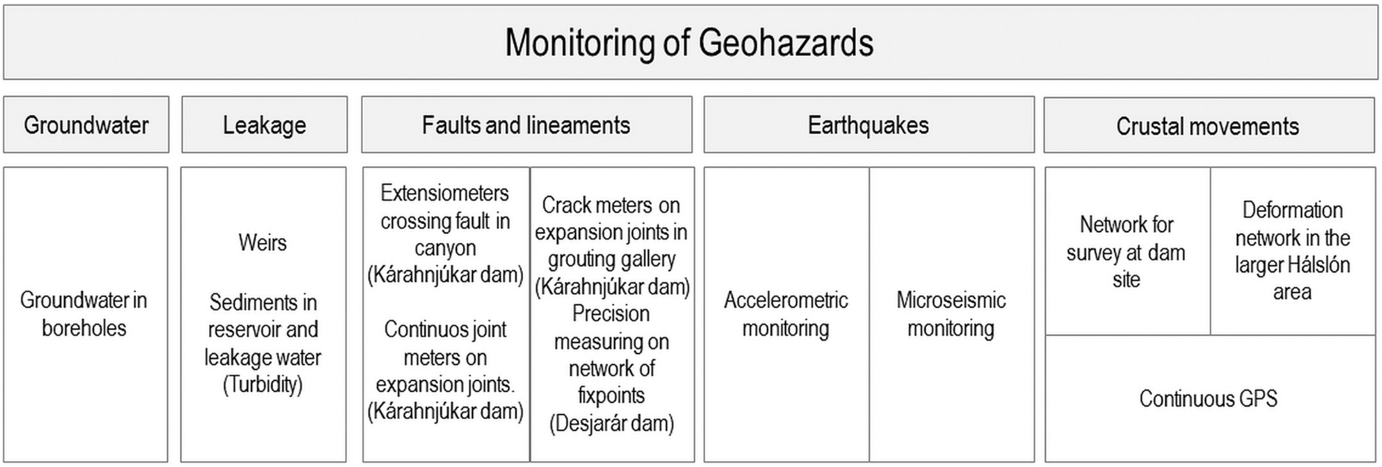


Fig. 9. Geohazard related monitoring.

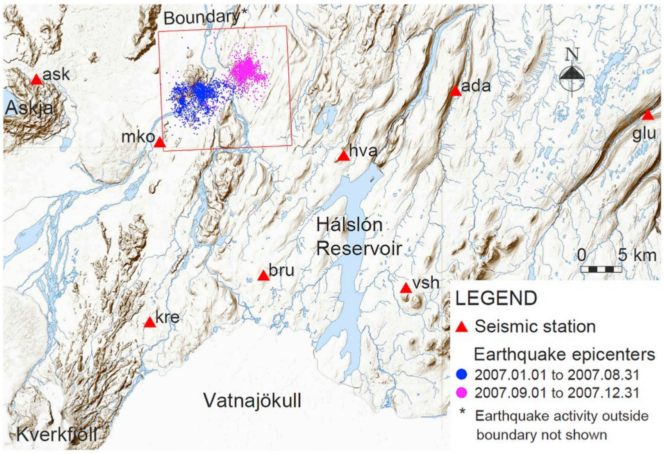


Fig. 10. Micro seismic stations (triangles) (Operated by the Icelandic Meteorological Office). The boxed boundary marks earthquake clusters recorded in 2007 in the Upptyppingar (blue cluster) and Álftadyngja (magenta cluster) region, only events ML ≥ 0.8 are included. (Earthquake data provided by the Icelandic Meteorological Office (Data submission no. 19-02-2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

several Continuous Global Positioning System (CGPS) stations were installed and two networks of benchmarks for Global Positioning System (GPS) surveying campaigns were set up, herein termed Near Dam Network and Reservoir Network. The two GPS surveying networks were linked by common observation points. The purpose is to observe surface deformations of the crust, caused by the hydrodynamic pressures due to the reservoir filling and increased overburden weight due to the dams. Furthermore, to monitor any ongoing other crustal movements, stress accumulation and/or alteration in the Hálslón area, including potential movement on the Sauðárdalur Fault (Fig. 5) or the faults beneath the

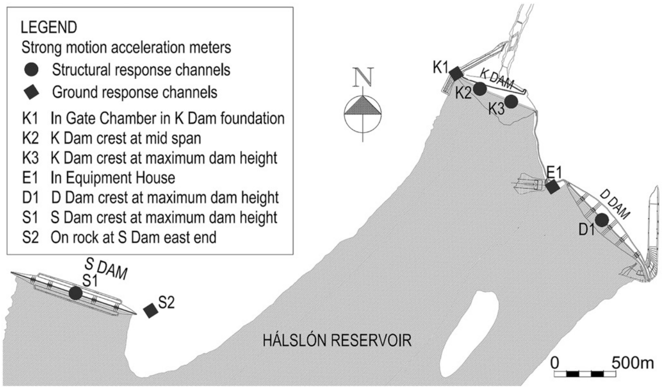


Fig. 11. Monitoring systems for strong ground motion and dam response. (Operated by the Earthquake Engineering Research Centre (EERC), University of Iceland).

Dams. The Reservoir Network (Fig. 12a) includes 35 benchmarks, which are distributed over a large area and connect to benchmarks in nearby volcanic systems. The Near Dam Network (Fig. 12b), includes benchmarks in the vicinity of the dam sites and was designed to monitor, firstly the impoundment induced deformation across the K- and D Dams, and secondly, subsidence in the three-dam area in the northern part of Hálslón.

(iv) Instruments were installed on or near each fault in the foundation of the K Dam to monitor potential movements, whereas only the most prominent fault in the foundation of the D Dam is monitored downstream of the dam. Joint meters and/or crack meters in the foundation of the K Dam are accessible in the grouting gallery underneath the main dam. The Toe-wall Fault or fault DF-1 (Figs. 6 and 7) is monitored by extensometers in boreholes crossing the fault (Fig. 13) but with different alignment in the horizontal plane.

(v) Instruments to monitor groundwater elevation were installed in > 30 boreholes in the reservoir area (Fig. 14), at dam sites,

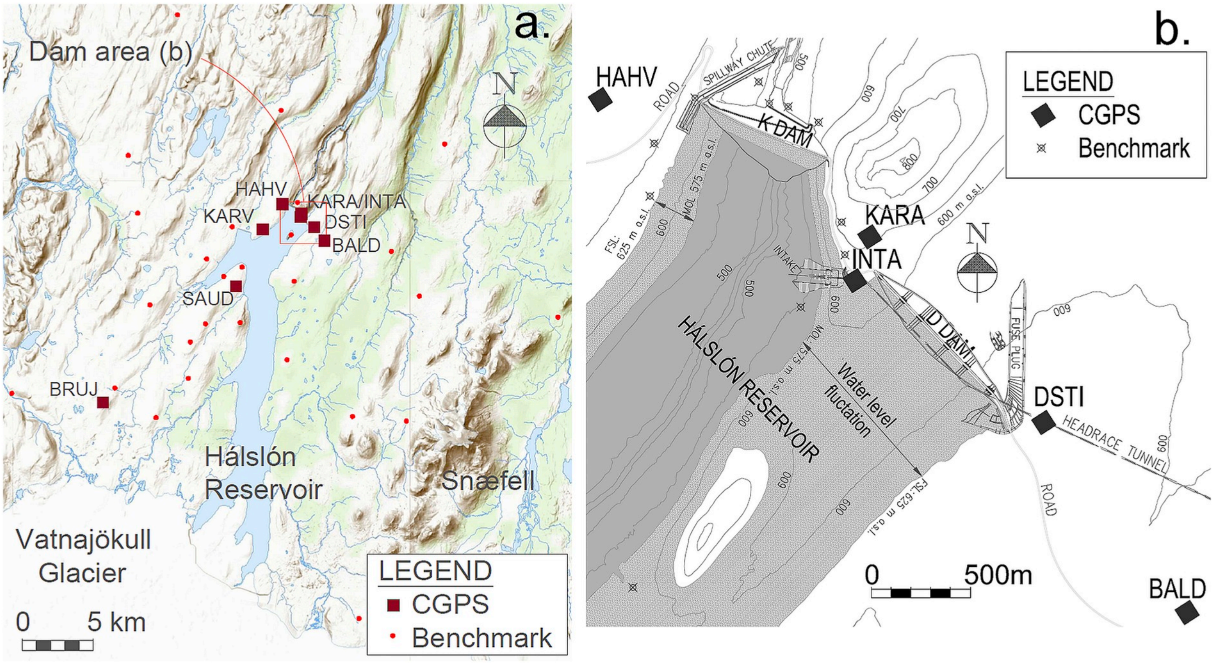


Fig. 12. Benchmarks and CGPS network. (a) The Reservoir Network: Benchmarks (red dots) used in surveying campaigns and CGPS stations (reddish boxes with labels). The boxed Dam area with the Near Dam Network is shown in Fig. 12b. (b) Near dam CGPS network. (Boxed dam area in Fig. 12a). (GPS benchmark campaigns and CGPS observations were operated jointly by researchers at the University of Iceland, the Icelandic Meteorological Office and Hnit Consulting Engineers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

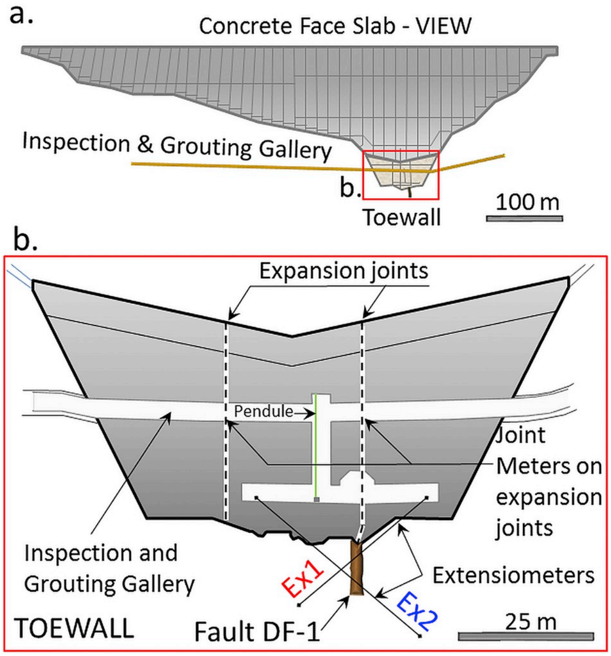


Fig. 13. Extension meters crossing the Toe-wall Fault, DF-1, in the foundation of the Kárahnjúkar Dam (K Dam) where the dam is highest (in the canyon). (a) Longitudinal view of the K Dam upstream face. (b) Instrumentation in the Toe-wall. (Dam instrumentation specified by the designer, Kárahnjúkar Engineering Joint Venture).

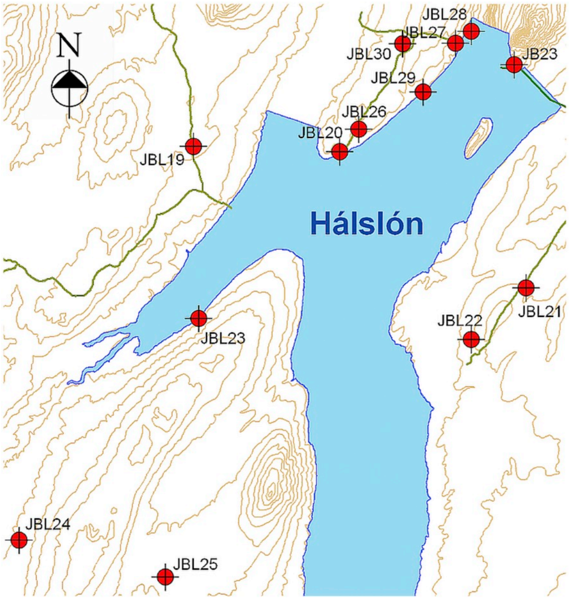


Fig. 14. Location of boreholes (JBL) for groundwater measurements. (Network operated by Landsvirkjun).

downstream of dams and along the headrace tunnel. These were installed to observe general changes in groundwater elevation in the Hálslón area due to the reservoir filling. The first instruments were installed in 1998 with boreholes added in 2005 and 2006. The purpose for the geohazard monitoring was partly to identify any causal relationship between the groundwater elevation and potential earthquake activity, as well as to observe any unusual changes in the observed parameters and potential indication of increased leakage.

(vi) Monitoring of leakage (or seepage) and its turbidity is one of the main factors in a comprehensive safety monitoring of a dam. In terms of geohazards, a sudden increase in leakage might be an indication of a fault opening in the dam/reservoir foundation. Whereas increased turbidity might be an indication of erosion or piping through the dam or its foundation. Leakage is measured at a weir provided downstream of each dam. Furthermore, flow measurements were conducted at few locations in the canyon

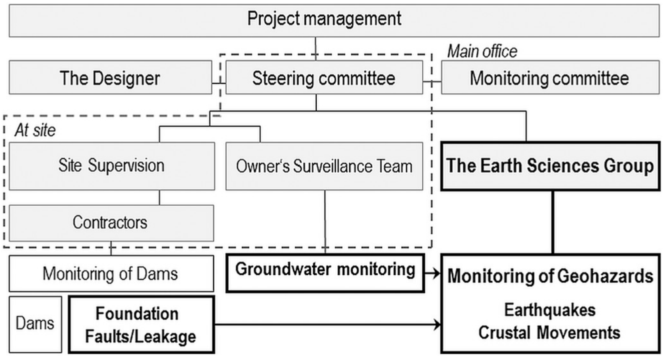


Fig. 15. Hálslón impounding, general organization.

downstream of the K Dam and the D Dam. Additionally, there are several locations in the tunnel system within the foundation of the K Dam where leakage is monitored.

In Table 3, the various monitoring networks are linked to the apprehensions and concerns on geohazards previously listed in Table 1.

4.2. Multidisciplinary organization

The general organization chart for the Hálslón Reservoir impounding is shown in Fig. 15. The Steering Committee was responsible for all actions taken at site during the impounding and was to be informed of all unusual activity in the Hálslón area. Representatives from both the site supervision (Supervision) and the dam designers (Designer) were in the Steering Committee while the chairman of the committee represented the owner of the project (Owner).

During the impounding period it was also decided, in view of potential geohazards, to involve scientists that were already familiar with the area and the project through their research and/or on-site operation of monitoring networks. For this purpose, a multidisciplinary team of specialists was established, termed the Earth Sciences Group (ESG). During impounding the ESG was to review monitoring data from geohazard related monitoring networks, submit status reports and provide consultation on geophysical issues, as well as potential warning procedures triggered by monitoring data or any observation of abnormal conditions.

During impounding, daily visual inspection of the dams and surrounding areas were carried out by the Supervision, while the contractors for the dams (Contractors) performed instrumentation readings (manual and/or automated). Reports from daily visual inspections and instrumentation readings were updated daily on an ftp site and then further transferred to the Owner's monitoring website. Monitoring of groundwater level was mostly automatic and supervised by the Owner's surveillance team, with the monitoring data assessable through the monitoring website. Furthermore, interested parties could view seismic parameters recorded by the micro seismic network and delayed time series of coordinates from Continuous Global Positioning System (CGPS) stations on a webpage, where registered activity was documented.

4.3. The Earth Sciences Group

The members of the earth science group (ESG) were specialists in one or more of the following fields: geophysics, geology, earthquake engineering and structural/dam engineering. The members represented institutions responsible for different instrumentation installed and/or had conducted site investigations and research in the Hálslón area for the KHP. In addition, a representative from the Designer was in the group to ensure focus on issues of relevance for dam safety. The role of the ESG was to meet regularly during the impounding and review

Table 4
Monitoring of earthquakes and crustal movements in the Hálslón area. Base conditions and information provided to the steering committee & others.

Instruments	Responsible	Base conditions[a]	Information level 1[b]	Information level 2[c]
Micro seismic stations	IMO	No confirmed seismicity recorded in the Hálslón area. Blasting frequently recorded. Vibrations recorded from the ongoing construction work.	Seismic activity recorded in the Hálslón area. Increased seismic activity in nearby volcanic systems.	Earthquake of magnitude M 2.5 or larger in the Hálslón area.
Strong motion accelero-meters	EERC	No earthquakes recorded. Blasting and construction related vibrations frequently recorded.	Earthquake recorded.	Recorded PGA ≥0.1 g in the Hálslón area.
CGPS stations	IMO	Average pre-impounding velocities and seasonal variations defined.	Change indicating crustal movements in the area.	Change showing definite crustal movements.
GPS Survey	EERC, IES	One campaign performed before impoundment	N/A (Yearly report)	N/A (Yearly report)

[a] Based on pre-impoundment monitoring data.
[b] Event reported by email.
[c] The chairman of the steering committee notified by phone. Event reported by email.

Table 5
Monitoring of groundwater, leakage, faults and lineaments. Base conditions and conditions for ESG review.

Instruments	Responsible[a]	Base condition	Conditions for ESG review[b]
Ground water level	Owner surveillance	Base conditions for each borehole defined.	Changes in ground-water level indicating increased leakage or relation to seismicity.
Extensometers on the Toe-wall fault	Contractor	No movements. Fluctuation in readings typically ± 0,15 mm.	Changes in monitoring data that might result in increased leakage or be related to seismicity.
Joint meter on faults	Contractor	No movement	Same as for extensometers.
Crack meters	Contractor	One reading (zero reading) available prior to impounding. No movements presumed prior to impounding.	Changes between readings data that might result in increased leakage.
Leakage	Contractor	N/A	Sudden increase in leakage or turbidity.

[a] Monitoring during impounding.
[b] Initiated by the steering committee or the Owner.

monitoring data relating to leakage, groundwater levels, earthquake activity and crustal movements in the Hálslón area (see Fig. 9). The objective was to be able to provide consultation regarding geophysical issues. Furthermore, to report any indications of potential reservoir triggered earthquakes (RTE) or critical crustal movements.

The ESG was also tasked to define pre-impounding base conditions in the Hálslón area considering potential geohazards (see Table 4). For this purpose, the team members were given access to all relevant data. This included: the seismic design criteria, the impounding manual, the monitoring and research program, groundwater measurements and modeling, leakage assessment, risk assessment, and reports on geology, earthquake hazards, crustal strain and fault movements.

The ESG issued regularly summary reports on the monitoring of geohazards for the period from start of impounding in September 2006 till the end of the first impounding cycle in December 2007. The last summary report was finalized in 2009, covering three reservoir filling cycles. Each summary report was provided as a single sheet table documenting overall status, supplemented with attachments reporting on various relevant issues in more detail. The ESG was active during the impounding and in the following two years after impoundment, while the cyclic process of impounding and discharging the reservoir was in progression. The geohazard monitoring systems at the Hálslón Reservoir and dams are still operated by the relevant institutes, but the multidisciplinary approach of reviewing the monitoring data is no longer in effect. This however could easily be revived.

4.4. Base conditions and information levels

Base conditions with regard to geohazard monitoring prior to impounding were defined by the ESG. The base conditions are given in Table 4, for the instruments monitoring potential earthquakes and crustal movements in the Hálslón area. Base conditions prior to impoundment for groundwater level and movements on faults and lineaments in the dam foundation are given in Table 5. These were originally defined by other consultants but were reviewed by the ESG members. Two different information levels were defined and are listed in Table 4 along with the base conditions. Information level 1, required a report on certain events to be sent by email from the party responsible for the monitoring to the Steering Committee, the Designer and the ESG. Information level 2, additionally required immediate report to the chairman of the Steering Committee by phone. The cases for which the review and assessment of the ESG might be requested were listed and are shown in Table 4 along with the base conditions. For example, an ESG review might have been requested in the case of sudden increase in leakage from the reservoir. The potential ESG task would then have been to assist in identifying and locating the source of the leakage, potentially along a fault or lineament.

5. Monitoring results

This section reports on the overall results from each monitoring network leading to the conclusions in Table 6. Table 6 also relates the monitoring results to the apprehensions previously summarized in Table 1 and provides the pre-defined design and safety limits for comparison with the data reported herein. Results from the monitoring programs hitherto, all indicate that the geophysical impact of the Hálslón Reservoir is well within the limits set prior to the impounding.

5.1. Seismicity

In the short period of monitoring prior to impounding no earthquakes were recorded in the Hálslón area. Conversely, blasting events were regularly recorded by the seismometric network throughout the construction period. During impounding, some minor events were detected on the network, mostly defined as frost breaks (icequakes) or events possibly caused by landslides in the canyon downstream the dam site. Two or three small events were defined as earthquakes but could not be related to the reservoir inundation with any certainty. The events detected by the seismometer network in the Hálslón area during the reservoir impounding are listed in Table 7. In the years since the start of impounding no earthquakes related to the reservoir have been reported to occur in the Hálslón area, although icequakes and a couple of microearthquakes have been recorded. None of the events listed in Table 7 were recorded by the accelerometers installed at the base and crest of the dams, as the intensity of motion detected by the seismometer stations was always below the triggering level set for the accelerometer instrumentation.

Earthquake activity in nearby volcanic systems was reported regularly during the reservoir impounding. The recordings followed a well-recognized and familiar pattern until February 2007 when an episode of earthquake activity started in a previously seismically inactive area within the Kverkfjöll fissure swarm. The activity started near Mount Upptyppingar, about 20 km NW of the dam site (see location of events labelled 2007: 01.01 to 08.31 within the marked boundary in Fig. 10), migrating with time towards north-east or Mount Álftadalsdyngja (events labelled 2007:09.01 to 12.31 within the marked boundary in Fig. 10) and progressing to shallower depth. The activity was described as concentrated clusters of deep seated (hypo-centric depth of 10–22 km), tectonic earthquakes generally < 2 in magnitude (see Jakobsdóttir et al. (2008) for details). The largest earthquakes were of local magnitude ML 2.3. More than 9000 earthquakes were located in this area from February 2007 to April 2008. In 2007, the year of the first filling of Hálslón, 5300 earthquakes were detected (Jakobsdóttir et al., 2008).

The detection of the earthquake activity was made possible by the installation of the seismic network installed for the project (KHP). It was thought unlikely or impossible that these tremors could be triggered or influenced by the Hálslón Reservoir considering that such relationship could not be physically explained. On the other hand, it was pointed out that reactivation of the Kverkfjöll fissure swarm should be of concern, considering that the Sauðárdalur Fault (Figs. 5 and 8b), in the Hálslón Reservoir is now linked to that fissure swarm.

Table 6
Limits defined for design/safety and results from monitoring linked to geological challenges/apprehensions listed in Table 1.

Nr.	Apprehension/challenges (see Table 1)	Defined design and safety limits (see Table 2)	Results from monitoring
A1	Reservoir triggered earthquakes (RTE)	RTE with PGA of 0.5 g used in seismic design.	No RTE measured on monitoring systems
A2	Excessive leakage	Design estimate: 5 m^3/s	Leakage was within design estimates
A3	Crustal deformations due to the reservoir may trigger volcanic eruption	Considered extremely unlikely.	Has not occurred
A4	Reservoir induced settlements (in meters)	Maximum reservoir induced settlement estimated to be 300 mm.	Settlement induced by the reservoir (14 ± 10) mm
A5	Movements on faults in the dam foundation of concern for safety	The design criteria allowed for a 10 cm maximum differential displacement across faults.	Reservoir induced movements have been measured near faults in the foundation of the Kárahnjúkar dam. A maximum potential opening across faults in the range 1 cm, has not led to increased leakage and is not of concern for the dam safety. Minor temporary opening of DF-2 during the initial impoundment, may have resulted in an insignificant temporary increase in leakage.
A6	Opening of faults in the reservoir and dam foundation (Toe-wall fault)	Design criteria allows 10 cm differential displacement.	Insignificant movement (not confirmed opening) has been recorded on instruments monitoring the Toe-wall fault.
A7	Near field earthquake action of concern for dam structures	Predicted earthquake originating on known faults with a PGA of 0.3 g.	Near field earthquake action of concern for dam safety has not been recorded hitherto.

Table 7
Seismic events detected by the monitoring system in the Hálslón area during impoundment.

Year Month	Description of the event detected
2006	
Oct	A small earthquake of magnitude M~1, was recorded at a depth of 17 km some 7 km ESE of the dam site. Highly unlikely to be related to the impoundment.
Nov	Three small shallow events were detected close to Vatnajökull Glacier, west of the reservoir, interpreted to be frost breaks, in accordance with the weather conditions at the time of occurrence.
2007	
Apr	Two shallow and small (~M0) events were recorded north of Kárahnjúkar. Possibly caused by a landslide or potentially related to the inundation.
July	Two small events (~ M1 or less) of low frequency content and hard to locate, were measured at the Vatnajökull Glacier nearby the Hálslón area. These might be icequakes.
Sept	An earthquake (~M0.7) was recorded about 2 km north of Kárahnjúkar dam at a depth of 0.1 km. Further five events, probably all icequakes, were detected in the ice catchment of Brúarjökull Glacier.
Nov	An event (~M0.5) was recorded close to the Karahnjukar dam at a depth of ~1 km.

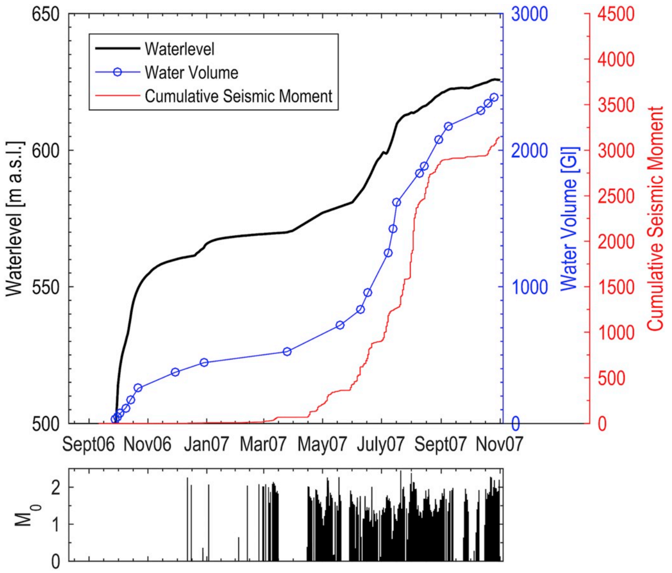


Fig. 16. Cumulative seismic moment at Upptyppingar, water level and volume of the Hálslón Reservoir between Sep 2006 & Nov 2007. (Adapted from a figure by the Icelandic Meteorological Office, which also provided the earthquake data).

The activity continued in 2007 and when the increase in seismicity was represented by a cumulative curve of seismic moment, it seemingly coincided with the water level increase during the then ongoing filling of Hálslón as shown in Fig. 16 (Roberts et al., 2007; Jonsdottir et al., 2007). Accordingly, it was stated by some geophysicists that a relationship to the reservoir impounding should not be ruled out without further monitoring and research. The proposed relationship was described as a mystery or it was suggested that magma flow could potentially be caused by even a minor subsidence of the crust due to the increasing weight of the reservoir, hence triggering these earthquakes.

This hypothetical relationship was doubted within the ESG based on the following arguments: There was no clear geophysical explanation for connection between the reservoir and the clusters at Upptyppingar some 15 km away. Annual crustal deformations due to seasonal change in the loading from the Vatnajökull glacier are much greater than any changes in the water level of Hálslón can cause. Potential water infiltration between the Hálslón area and the Upptyppingar area was highly improbable considering orientation of lineaments and the well-established fact that the two are different catchment areas. Statistical analysis by independent experts concluded that reservoir triggering of the earthquakes could not be confirmed. Finally, it was pointed out that cumulative curves tend to rise, for example in the way shown by Fig. 16.

The earthquake activity continued into 2008 while the reservoir elevation decreased, and thus the similarity between the curves in Fig. 16 was lost, and the discussion expired. Furthermore, in early 2008 after processing data from a surveying campaign to monitor crustal displacements of benchmark points, the activity (within the marked boundary in Fig. 10) was explained as a geophysical process unrelated to the reservoir filling. The micro seismicity recorded had to be interpreted in connection with the monitoring of crustal movements to fully understand the ongoing processes.

During the impounding period, the apprehensions put forward during the preconstruction phase, were revived and dealt with rationally, in a similar manner. For instance, those concerning reservoir triggered earthquakes and reservoir induced crustal movements triggering volcanic activity.

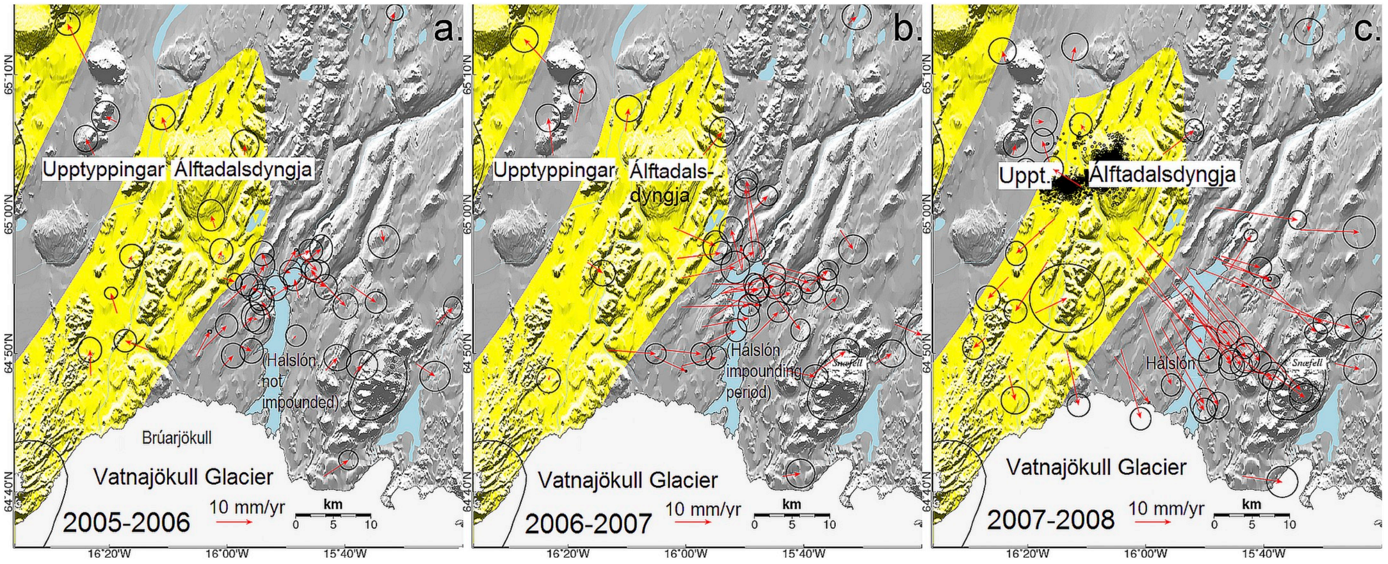
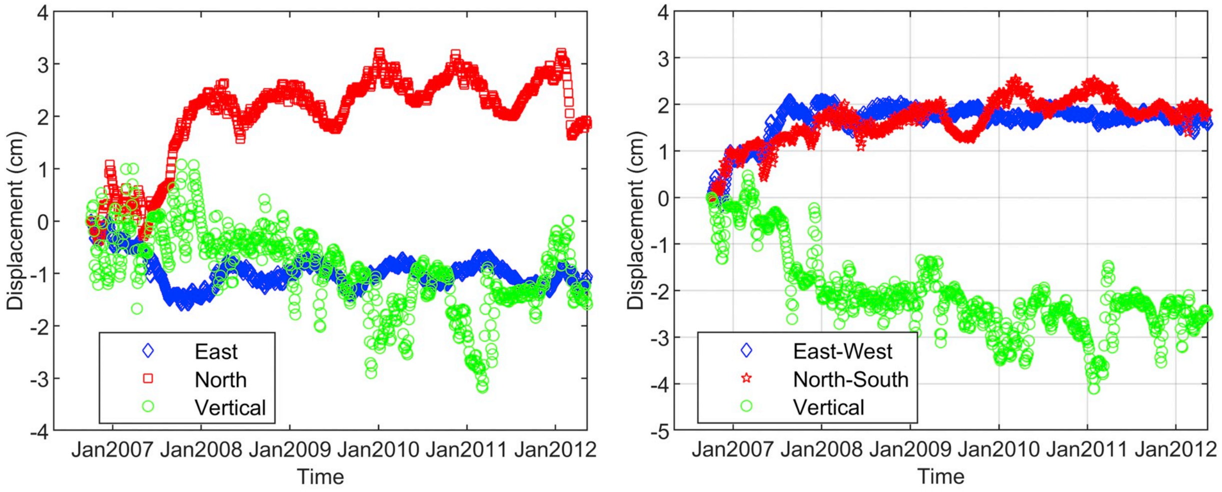


Fig. 17. Horizontal velocities derived from yearly GPS campaigns on the Reservoir Network between 2005 and 2008 (Ófeigsson et al., 2009). (Courtesy of Benedikt Ófeigsson).



(a)

(b)

Fig. 18. Results from selected CGPS stations in the Near Dam Network. (a) Displacement in east, north and vertical direction at CGPS station HAHV west of the K Dam, sampled at 2 values per week from the start of reservoir impounding. (b) Differential horizontal and vertical displacement between the CGPS stations HAHV on the west bank and KARA/INTA on the east bank of the K Dam, sampled at 2 values per week.

5.2. Crustal movements

GPS-campaigns were conducted on the Reservoir Networks (Figs. 12a and 17) in August of 2005 and 2006 prior to impoundment, in Sept. 2007 with the reservoir almost full (water level 622 m a.s.l.), in August 2008 and 2009 (Ófeigsson et al., 2010). In addition to this, three CGPS stations (see Fig. 12) were installed in 2005, with additional stations on each side of the Dams installed prior to the impoundment in 2006. They continuously monitored the crustal movements during the first impoundment cycles and some of them are still in operation.

Prior to the reservoir inundation, in the period 2005–2006, vertical crustal movements in the Hálslón area were observed from CGPS monitoring data from stations BRUJ, SAUD and KARV (see location in Fig. 12a). Firstly, there was an uplift of (15 ± 8) mm/yr related to a decreasing load on the crust from the nearby Vatnajökull ice cap, and secondly seasonal variations due to the annual change in snow load. The average uplift rate close to Hálslón reduced to (2 ± 7) mm/yr in 2006–2007, suggesting an average measured subsidence of (14 ± 10) mm due to the reservoir filling (Ófeigsson, 2008). These results confirmed that apprehension A4 in Table 1, put forth prior to construction predicting potential large reservoir induced settlements measured in meters, was not warranted. Furthermore, data from CGPS station HAHV and KARA/INTA and DIST, installed shortly before impounding on either side of the two main dams (for location see Fig. 12b), showed only very minor vertical movement of the order of a cm, as shown in Fig. 18a for CGPS station HAHV on the westerly side of the K Dam.

Reservoir induced horizontal movement was detected on CGPS station KARV (see location on Fig. 12a) during the first month of the filling amounting to a 6 mm westward movement in January 2007 of the total 8 mm reported by the end of 2007 when it strangely reversed its movement to the east. CGPS Stations SAUD and BRUJ (Fig. 12a) on the other hand did not show horizontal movements until in June 2007 when they showed an increased movement rate to the SSE and SE respectively (see Jakobsdóttir et al. (2008) and Geirsson et al. (2010) for details). This eastward movement in 2007 was contrary to what could be expected from the reservoir inundation. Thus, by the end of the first filling of the reservoir the CGPS monitoring of horizontal movements in the larger Hálslón area showed somewhat puzzling movements that could not by any logical reason be induced by the reservoir. GPS survey data covering a larger area was required for a more complete picture.

In 2008, the processing of survey data on the Reservoir Network revealed crustal movement extending from the Upptyppingar-Álftadalsdyngja area (U-Á area) (see Fig. 17) (Ófeigsson et al., 2009). Additionally, InSAR (Interferometric Synthetic Aperture Radar) interferograms showed a broad inflation extending from the U-Á area into the Hálslón area. This inflation and the earthquake clusters detected in the U-Á area in the period between February 2007 and April 2008, have been interpreted to be due to a magma intrusion beneath Álftadalsdyngja (Hooper et al., 2011; Jakobsdóttir et al., 2008; Martens et al., 2010; Martens and White, 2013). Hence, the movements observed in the vicinity of Hálslón Reservoir during 2007 were partly due to the inflation caused by this intrusion. Thus, monitoring the crustal movements aided in explaining the cause of the micro seismicity in the U-Á area and showed that this was caused by subsurface magma intrusion, but not the reservoir impounding.

The reservoir induced horizontal deformation across the Hálslón Reservoir upstream of the Kárahnjúkar dam (K-dam) was observed by GPS campaigns on the Near Dam Network and CGPS observations at stations KARV, HAHV, KARA/INTA and DIST (Fig. 12b). The measured deformations suggest widening of the Hálslón canyon with increased water level during the first reservoir impounding, a trend which may be intensified by the faults underlying the Hálslón Reservoir and the foundations of the dams. This effect was for instance noticed at CGPS Station HAHV, as shown in Fig. 18a, where the benchmark had moved up to 3 cm towards north and 1.5 cm towards west at the end of the first impoundment in October 2007. During the impoundment of the reservoir, the main orientation of crustal movement was between southwest and northwest at HAHV and from southeast to northeast at INTA and DIST, i.e. in all cases more or less across the canyon. Since the first impoundment the location has been more or less stable except for the effects of the annual reservoir filling cycle (see Fig. 2b), which is reflected in the data, especially through the north component. The peak to peak annual variation is in the order of 1 cm (see Fig. 18a).

The development of differential displacement across the K Dam canyon in the period September 2006 to January 2012 is shown in Fig. 18b. The canyon gradually widens during the impounding and moves towards north under the pressure from the water in the reservoir, resulting in a roughly 3 cm total differential displacement between stations HAHV and KARA/INTA, combining the north and east components. After the first impounding, no further permanent movement is observed, only seasonal variations. As the longitudinal axis of the K Dam lies more or less in east-west direction, the east component gives the best estimate of the actual widening of the canyon and thereby possible opening of faults. It is observed in Fig. 18b, that the east-west differential displacement across the K dam is roughly 2 cm after the first impounding and no permanent increase is observed since. A further east-west differential movement of about 1 cm was observed across the D Dam from early June 2007.

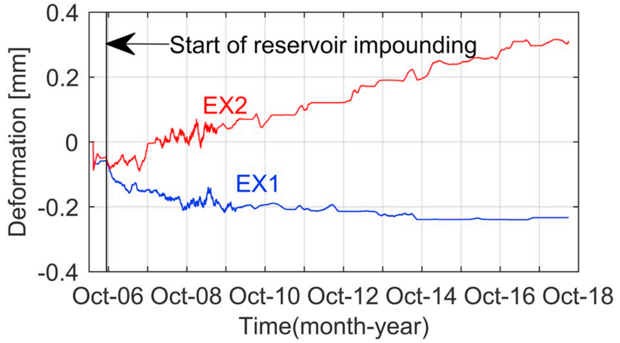


Fig. 19. Monitoring of fault DF-1 (the Toe-wall Fault), with extensometers (see Fig. 13) EX1 and EX2 (original data filtered with a moving average filter with a span of 5%). Negative and positive values respectively indicate tension and contraction.

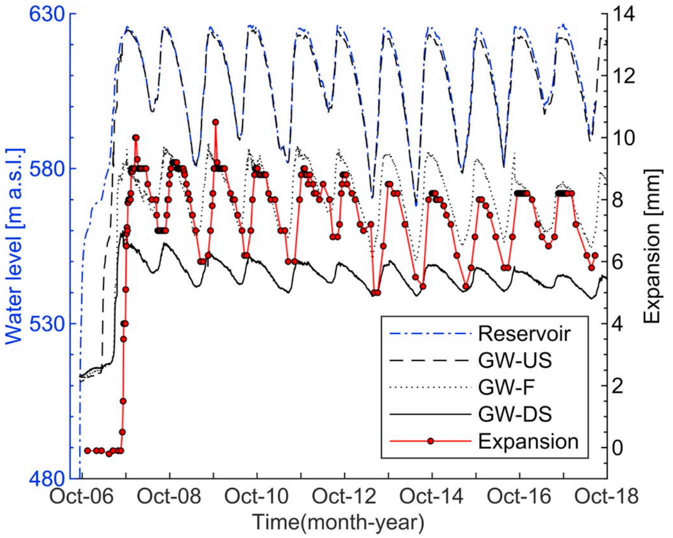


Fig. 20. Measured expansion of movement joint in the grouting gallery of the K Dam near fault DF-3 (see Fig. 4) plotted with groundwater level measured at the fault location, as well as the reservoir water level.
The groundwater pressure is measured at the Fault DF-3 (GW-F), as well as upstream (GW-US) and downstream (GW-DS) the grout curtain at the DF-3 location (see Fig. 4).

5.3. *Fault movement*

During and after the impounding, insignificant or minor movement has been detected on instruments monitoring fault movement. The deformation recorded since start of impounding in 2006 to 2009, along the two extensometers crossing the Toe-wall Fault, DF-1 (Fig. 13), is insignificant or < 0.3 mm on each (see Fig. 19). The extensometer EX2 measures subtraction while the EX1 measures extension, considering the alignment of the extensometers this indicates either vertical differential displacement and/or horizontal sliding. However, the movement is insignificant, and the measurements may be influenced by movement of the Toe-wall itself. The insignificant movement is confirmed by other deformation measurements in the Toe-wall. However, there have been movements detected near faults labelled DF-2 and DF-3 in the K Dam foundation. The movement observed near fault DF-2 occurred in 2016 and was an opening in the order of 1 mm which coincided with a sudden increase in water pore pressure. The water pressure was relieved after the measured fault opening and dropped considerably or to a level monitored in 2008. No external trigger could be identified. Some temporary minor increase in leakage was noted following this movement of fault DF-2. The largest persistent movement is detected near fault DF-3, or an expansion in the order of 10 mm. The expansion is measured manually on a simple standard concrete crack monitor installed on a movement joint in the grouting gallery near the fault. The movement follows, with a slight delay, the measured groundwater level at the fault location, which in turn follows the reservoir level as can be seen on Fig. 20. A slight decrease in the response with time can be noted for both the groundwater pressure downstream (GW-D) as well as the measured expansion. The groundwater pressure measured at the fault location (see Fig. 20) is further discussed below. The measured movement is within design limits, but the dam design allows for up to 100 mm expansion on individual faults and movement joints within the structure.

Monitoring of the most profound fault in the foundation of the

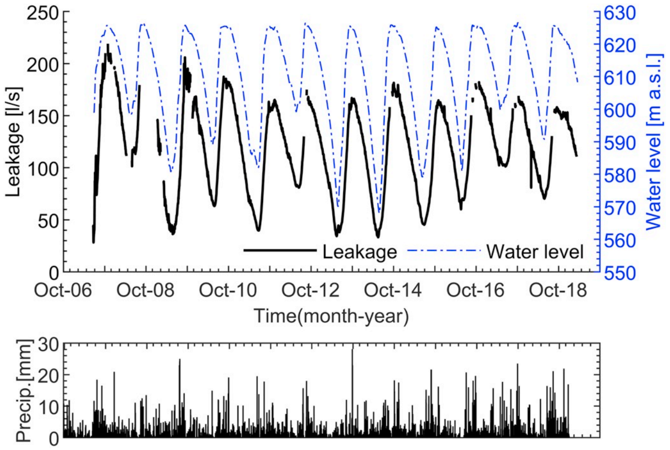


Fig. 21. Leakage measured at the downstream toe of the K dam plotted as a function of time along with the seasonal variations in the reservoir water level and daily precipitation (precip.) (Precipitation data is from a weather station in the area operated by the Icelandic Meteorological Office).

Desjarár dam implies subtraction but the movement is insignificant.

The results from monitoring the faults in the dam foundation provide direct answers to apprehensions A5 and A6 listed in Table 1. Confirming that the fault movements are insignificant and hitherto not of concern for dam safety.

5.4. Groundwater and leakage

Groundwater elevation has been monitored in numerous boreholes around Hálslón Reservoir, since 1998. The groundwater table prior to impounding was drawn from these measurements and is shown in Figs. 5 and 7. During and after impounding, the monitoring revealed that the reservoir elevation in general only affects the groundwater table where the water level rises above the groundwater elevation as it was prior to impounding. For instance, at the reservoir banks, where the groundwater table is lower than the annual variation in the reservoir elevation, the monitoring data follows the reservoir water level (Axelsson, 2013). Hence, no unexpected changes have been observed from the monitoring data. The reservoir elevation governs the groundwater table in the dam foundation as well as at the reservoir bank. Precipitation (see Fig. 21) does not directly influence the groundwater table in the dam foundation, since this accumulates into the reservoir above the measuring location. In general, the effect of precipitation on the groundwater table at the reservoir banks is negligible and insignificant for the geohazards considered here in comparison with the inflow of glacial melt water into the reservoir.

Fig. 20 displays groundwater pressure measured at the fault DF-3, presented as groundwater level. The figure is presented both as an example of the variation in the groundwater level with the reservoir water level (RWL) and to demonstrate this relation at a fault location. The groundwater level is measured by piezometers located upstream (denoted GW-US on Fig. 20) and downstream (denoted GW-DS on Fig. 20) the grout curtain at the fault location, as well as within the fault DF-3 (denoted GW-F on Fig. 20). The groundwater level upstream the grout curtain is nearly identical to the reservoir water level, although the peak response has slightly reduced with time. Furthermore, there is a head drop across the fault (GW-F) from the upstream (GW-US) to the downstream (GW-DS). The response to the reservoir elevation measured by the piezometers has reduced with time, indicating self-sealing of the foundation from the high sediment content of the water in the reservoir, which is fed by glacial rivers. The reduction is strongest for the downstream piezometer (GW-DS). Similarly, the movement measured in the grouting gallery (see expansion in Fig. 20) has decreased.

Measured leakage has been in the order of about 200 l/s at the downstream toe of the Kárahnjúkar (K) dam (see Fig. 21) and roughly 50 l/s downstream the two saddle dams, respectively. The leakage follows the reservoir elevation as evident from Fig. 21 showing measurements downstream of the toe of the K dam, along with the reservoir level and daily precipitation. The daily precipitation for the period shown is on the average 1.24 mm with a standard deviation of ± 2.58 mm, with occasional peak values between 20 and 30 mm. The daily precipitation has insignificant influence on the overall leakage measurements. The gaps in the leakage data observed from the figure are mainly due to difficult instrument operational conditions during periods of reservoir spilling. The leakage at the highest reservoir elevations is seen to gradually decrease with time, again indicating self-sealing of the dam foundation as mentioned above. The total leakage further downstream the reservoir is difficult to measure but is estimated based on available measurements to be less than the 5 m^3/s predicted prior to impounding. Additionally, turbidity is measured in the reservoir and the seepage water, and no unexpected changes or trends can be noted from the monitoring data.

The time-series of both leakage and turbidity data, show a pattern of response to the reservoir elevation in line with the behavior shown in Fig. 21. However, no long-lasting trends have been observed indicating undesirable processes ongoing in the dams or their foundation, such as erosion or gradually increasing opening of lineaments. In conclusion, the leakage is well within acceptable limits. Thus, the leakage measurement provided answer to the question inherent in apprehension A2 in Table 1, on leakage.

6. Discussion

Establishing a group of specialists, the Earth Science Group (ESG), as a part of the Hálslón impounding organization, turned out to be an effective venue for discussing and debating the potential geohazards in the area. Such a multidisciplinary approach is highly recommended for mega projects facing geohazard related challenges as well as those where potential effects on the geoenvironment are being disputed. The discussions within the ESG took place mostly parallel to the process of construction and impounding and did not interrupt the operations ongoing at the construction site. However, representatives from both the Designer and the Owner, along with a special panel of three international experts appointed for the project, were well informed and took part in the discussions on monitoring issues, interpretation of geohazards and the potential threats facing the dams and the reservoir. Even though consensus might not have been reached on all aspects, constructive discussion raised the level of knowledge on the subjects at hand as well as awareness regarding the various topics addressed.

The approach taken in the design of the geohazard monitoring as well as the multidisciplinary methodology described has, e.g. through identification of the apprehensions in Table 1, elements that are compatible with a potential failure mode analysis (PFMA) (see e.g. Hariri-Ardebili et al. (2016), FERC (2017) and a joint publication by USBR and USACE (2015), and). Comprehensive implementation of a PFMA in a project facing geological challenges advances the approach described in this paper. This would set a clearer focus for any multidisciplinary group of specialists when reviewing relevant background information as those made available to the ESG (see Section 4.3), as well as in the analysis and review of the monitoring data. A systematic identification of potential failure modes combined with the methodology described by Sigtryggsdóttir et al. (2016), should enhance the design of the monitoring systems as well as aid in defining alarm values and/or alarming trends in the collected data. This should further assist in identifying potential interrelation between data from different processes. Thus, there are clear benefits in the use of a PFMA, while the limitations are related to the quality and extent of data and information available, as well as the knowledge and experience of the specialists performing the analysis.

The case study presented, demonstrates that complications due to geohazards related to tectonics can arise even in an area generally assessed as a low seismic area. Important for the Kárahnjúkar Hydropower Project (KHP) in this respect was the conservative design criteria developed during the pre-construction phase considering a maximum credible earthquake (MCE) event in the approximate dam area as well as a reservoir triggered earthquake (RTE). Consequently, the reevaluation of the earthquake action had insignificant effects on the dam design. When pre-construction geological investigations are constrained environmentally or limited by difficult access it is generally sensible to make conservative design assumptions to account for unexpected geological findings. In this respect it should be noted that for dam design it is recommended to consider a MCE, event originating on a recognized fault in the reservoir area or within a geographically defined tectonic province (ICOLD, 2016). Thus, favoring safety, one may apply an improbable earthquake that does not necessarily comply with the general seismic hazard zoning of the site area.

In ICOLD bulletin no 148 (ICOLD, 2016) it is recommended that a regional geological study area should cover as a minimum a 100 km radius around the dam site. This case study brings forth the relevance of this recommendations. While reconnaissance geological mapping for the KHP covered a large area, geological investigations of faults and lineaments during the pre-construction phase mostly focused on the construction area of the dams. Hence the Sauðárdalur Fault (Figs. 5 and 8b) was not recognized as active fault until additional geological investigations were instigated during the construction phase.

One of the lessons learnt from the KHP is that when conducting geohazard assessment it is of key importance to distinguish between scenarios that are considered possible and those that are probable. Invaluable for this purpose is the scientific work conducted, either in the field obtaining information relevant for further analysis and assessment, or analytically using numerical analysis and simulation leading to quantitative information that can be applied in design and used for reassessment of safety and risk. The scenarios deemed probable need to be assessed and their effect on dams and overall reliability analyzed. However, additional scenarios that may be possible, although improbable, still need to be considered within reasonable limits as is, for example recommended by ICOLD regarding the definition of a MCE event (ICOLD, 2016). It is important in this respect to recognize that a systematic monitoring of the relevant processes can involve both probable and improbable scenarios.

7. Concluding summary

The results from the monitoring programs, discussed and shown in Section 5, all indicate that hitherto the geophysical impact of the Hálslón Reservoir, the main reservoir of the Kárahnjúkar Hydropower Project (KHP), is well within the limits given in Table 6, which were set prior to the impounding. Only few micro earthquakes have been detected in the Hálslón area and none can be associated with the inundation. Furthermore, the seismicity of the area has not been altered by the reservoir. During the impounding, movement of magma within an active volcanic zone was detected by earthquake clusters 20 km N-W of the reservoir. These clusters were allegedly linked to the reservoir impoundment to begin with, but later found to be due to magma intrusion in the area (Jakobsdóttir et al., 2008; Martens and White, 2013) with a crustal inflation extending into the Hálslón Reservoir area. The inflation was detected by instruments monitoring crustal movements, set up as part of the geohazard monitoring systems related to the KHP. Thus, monitoring crustal movement was important in explaining this unusual micro seismic activity and in confirming that it was not triggered by the reservoir. The observed crustal movements in the reservoir area are less than predicted before the start of impounding. The average subsidence of the dam area was measured to be in the order of 1 to 2 cm due to the reservoir filling (Ófeigsson, 2008) compared to a numerical estimate of 30 cm and speculative apprehensions suggesting meters (see A4 in Table 1). Displacements across lineaments and faults in the dam foundations are well within design limits and correspond well with numerical estimation (Snæbjörnsson et al., 2006). The largest fault opening measured is within 10 mm compared to the 100 mm allowed for in the design. However, the movement measured on the Toe-wall Fault (DF-1) in the canyon crossed by the mega dam, Kárahnjúkar CFRD (K dam) is insignificant. Finally, changes in the groundwater level are as expected and leakage is well within acceptable limits.

In the process of defining a suitable geohazard monitoring for future mega projects facing geological challenges, a potential failure mode analysis in combination with the systematic methodology presented by Sigtryggsdóttir et al. (2016) comprising a reusable template, is highly recommended. Furthermore, an organization of the geohazard monitoring with the involvement of an Earth Science Group, as for the case presented here, is further recommended in the implementation and operation of the geohazard monitoring system. Moreover, it is important for every project involving reservoirs and dams, to have apprehensions regarding potential geohazard expressed and questions raised by experts and the public alike. It is equally important to provide answers to those questions either by numerical assessment or monitoring of relevant features. Some of the concerns raised on potential geohazards for the KHP can be considered unwarranted, but others were certainly relevant. In any case, the concerns raised were a positive driving force for a careful review of geohazards and other available information. Furthermore, this influenced the decision to establish a multidisciplinary monitoring program focusing on potential geohazards in a more holistic manner than perhaps would have been realized otherwise.

The monitoring of geohazards for Hálslón, the KHP main reservoir, has indeed answered the most urgent questions and concerns raised prior to and during impounding. The case study presented, thus demonstrates that a monitoring program set up to guard safety and reliability may also be important to provide required information on geoenvironmental impact not only for scientific interest but also for public information.

Today (in the year 2019) the monitoring systems are still in operation. However, it is of concern to the authors that a systematic review of the data is no longer in effect. It is a common situation, that a normal operation, in this case for over a decade, may give the sensation of stable conditions and safe structures. Consequently, less attention is given to both the monitoring of geohazards and data analysis as time passes. Therefore, a potential alarm for hazardous events, inherent in the monitoring data, may not be recognized.

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