

Hydropower dams in the Land of Ice and Fire

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ABSTRACT

Iceland's development from being one of Europe's poorest countries, at the onset of last century, to one with a very high standard of living is directly associated with the utilization of its renewable energy sources. In this development, dams have been indispensable in harnessing glacial rivers and mountain streams for hydropower. The dams retain storages for Iceland's melting glaciers/ice, however at the same time they may be located in the threatening settings of active tectonics and volcanism. In Iceland there are 29 large dams, as per ICOLD (International Commission on Large Dams) register of large dams. These are all built for hydropower generation and include 7 earthfill dams, 17 earth-rockfill dams, 3 rockfill dams and 2 concrete dams. The highest of these is a concrete faced rockfill dam, the Kárhnjúkar dam, about 200 m high. In addition to the 29 large dams, numerous small dams belong to the hydropower system that connects to the national power grid. In this paper Iceland's hydropower development is reviewed with focus on large dams, particularly earth-rockfill and rockfill dams. Challenges relating to: glacial, volcanic, tectonic, and seismic settings are discussed on general terms along with relevant design criteria and/or measures.

Keywords: Iceland, renewable energy, dams, geohazards.

1 INTRODUCTION

Iceland is often referred to as the Land of Ice and Fire. The former from its glaciers and ice caps. The latter, from its location as a volcanically and tectonically active island on the Mid-Atlantic Ridge. These two elements, ice and fire, are also sources for renewable energy, hydro and geothermal, currently providing 85% of the primary energy used in Iceland (see Fig. 1). The share of, hydropower and geothermal, in this is respectively; 20% and 65%.

Iceland's development from one of Europe's poorest countries, at the onset of last century, to a one with a high standard of living is directly associated with the utilization of its renewable energy sources. Geothermal energy is mainly used for district heating while hydropower is the main provider of electricity. Hydropower currently provides 73% of the total electricity production (see Table 1). Substantial amount of Iceland's precipitation is stored in ice caps, glaciers

and groundwater. This combined with extensive highlands, has enormous energy potential assessed up to 220 TWh/yr. However, considering feasibility and environmental constraints it has been estimated that 30 TWh/yr of hydropower could be produced (Bárðardóttir, 2006). This can be compared to the current energy production from hydropower of 12,9 TWh/yr. The first hydropower station (6 kW) was established in 1904. The ensuing decades, or till the 1950s, a number of small hydro were constructed. Subsequent hydropower development (see Fig. 2), with large-scale hydropower stations requiring large dams, followed in response to the establishment of energy intensive industries, such as aluminium smelters (Sigurðsson, 2002). The first large-scale station, Búrfell harnessing the Þjórsá River in South Iceland, was completed in 1969-1972 then with installed capacity of 210 MW (currently 270 MW). Enlargement of this station (100 MW) is in the construction phase.

In Iceland’s utilization of renewables, dams have been indispensable in harnessing the glacial rivers and mountain streams for hydropower. The largest dams generally retain storages for Iceland’s melting glaciers/ice, however at the same time they may be located in the threatening settings of active tectonics and volcanism. In this paper the focus is on large dams in Iceland, an overview is given along with the general design criteria. Challenges relating to; glacial, volcanic, tectonic, and seismic settings are discussed.

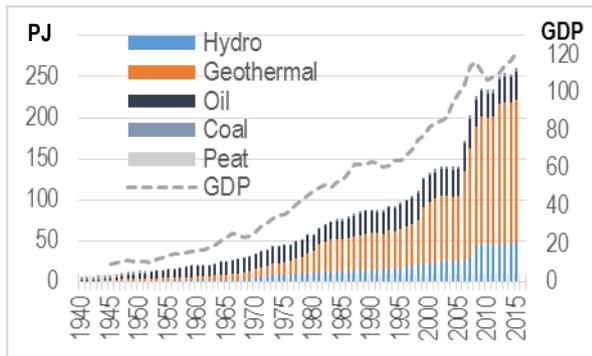


Figure 1 Primary energy use in Iceland’s (PJ) 1940-2015 along with Gross Domestic Production index (GDP). (Data: Orkustofnun and Hagstofa Íslands).

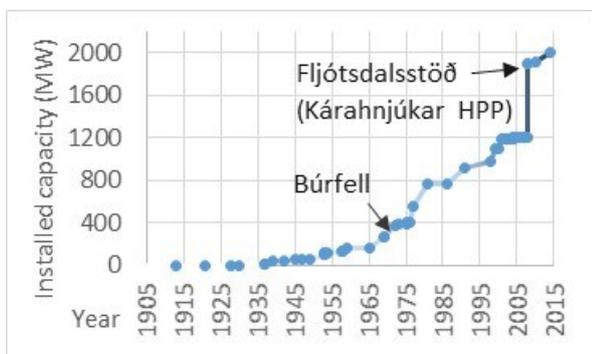


Figure 2 Installed capacity from hydroelectric power stations.

Table 1 Generation of electricity in Iceland 2015. (Orkustofnun, 2016).

	Installed		Production	
	MW	%	GWh	%
Hydro	1986	71,7	13780	73,3
Geothermal	665	24,0	5003	26,6
Fuel	117	4,2	4	0
Wind	3	0,1	11	0,1
Total	2771	100	18798	100

2 DAMS IN ICELAND

According to ICOLD (International Commission on Large Dams) register of large dams, there are 29 large dams in Iceland (ICOLD, 2016). Update of this number is required, but the discussion in this paper will comply with ICOLD registry. The National Power Company of Iceland (Landsvirkjun) is the owner of all but two of the large dams.

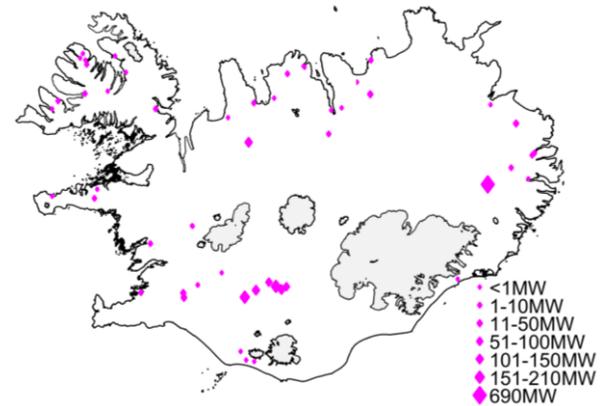


Figure 3 Hydropower plants in Iceland.

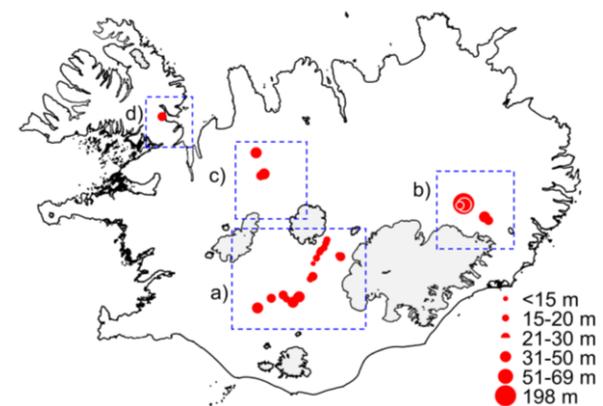


Figure 4 Large dams in Iceland : a) In South- and Mid-Iceland, in the Þjórsár-Tungnár catchment area. b) In East Iceland, in the catchment area of Jökulsá á Dal og Jökulsá á Brú. c) In North-West Iceland, in the Blanda catchment area. d) On the Vestfirðir Peninsula. Maximum dam height is indicated by marker size, see legend.

A large dam as per ICOLD definition is one which is: (a) more than 15 m in height measured from the lowest point of the general foundations to the crest of the dam, (b) more than 10 m in height provided they comply with at least one of the following conditions: (i) the crest is not less than 500 m in length (ii) the capacity of the reservoir

formed by the dam is not less than 1 million m³ (iii) the maximum flood discharge dealt with by the dam is not less than 2000 m³/s, (iv) the dam is of unusual design. The first large dam in Iceland was built in 1945, the 33 m high Skeiðsfoss concrete buttress dam in North Iceland. Second is the Búrfell dam completed in 1969. Subsequent construction of large dams followed the hydropower development shown in Fig. 2. Icelandic large dams are all built for hydropower generation and include 7 earthfill (TE) dams, 17 earth-rockfill (ER) dams, 3 rockfill (RF) dams and 2 concrete dams (ISCOLD, 2016; Pálmason, 2016). The highest of these is the Kárhnjúkar concrete faced rockfill dam, 198 m, completed 2007. In addition to the large dams, numerous small dams belong to the hydropower system of 59 stations that connect to the national power grid (Fig. 3). Official information on the small dams is not available in one place, and thus not the exact number of this. Furthermore, national regulations on dam safety do not exist. Here the focus is on large fill dams.

2.1 Large fill dams in Iceland

The most common earth-rockfill dams in Iceland have a central impervious core, abutted by gravel filters, supporting fills and riprap for erosion and wave protection (see Fig. 5). Filter criteria has generally considered these presented by Sherard and Dunnigan (1989).

The criteria set for slope stability of the large earth-rockfill dam at the different design stages has generally been set as follows:

Construction stage, completed dam	
Empty reservoir	$F_s \geq 1.4$
Critical reservoir level	$F_s \geq 1.4$
Steady stage, finished dam	
Full reservoir,	$F_s \geq 1.5$
Empty reservoir,	$F_s \geq 1.5$
Rapid reservoir drawdown, finished dam	
Long term pore pressure	$F_s \geq 1.3$
Earthquake	
Crest/slope displacement,	<0.3 m

Example material properties for stability considerations are presented in Table 2.

In dam design and re-evaluations on flooding, the trend the past few years has been, to follow more directly the criteria set by Norwegian regulations on dam safety (Forskrift om sikkerhet ved vassdragsanlegg).

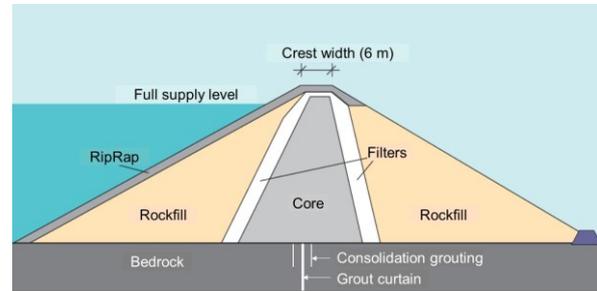


Figure 5 Typical cross section of an Icelandic Earth-rockfill dam

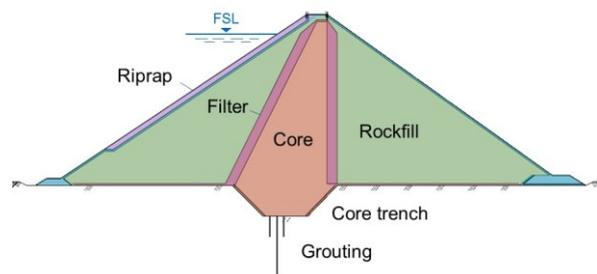


Figure 6 Example cross section of an Icelandic earth-rockfill dam with a core trench.

Table 2 Example material properties

	Density [kN/m ³]		Cohesion [kN/m ²]	Friction angle [°]
	Saturated	Moist		
Core*	22		0	40-42
Shell**	20-21	19	0	>45

*Morain; **Rockfill, generally pillow lava.

The dam slopes of the Icelandic dams vary somewhat, although there is a clear relation to dam type (fill material), or as follows: Earthfill dams have generally an upstream slope (U/S slope) of 1:2.2 and downstream slope (D/S slope) of 1:2. Earth-rockfill dams built in Mid, South and North-East Iceland typically have an U/S slope of 1:1.8 and D/S slope of 1:1.6. The most recent earth-rockfill dams, built in East Iceland generally have an U/S slope of 1:1.5 and a D/S slope of 1:1.4. The rockfill dams with the impervious element on the U/S slope have somewhat steeper slopes upto U/S slope of 1:1.3 and D/S slope of 1:~1.25 (the Kárahnjúkar CFRD).

The rock, used in the Icelandic rockfill dams and the supporting zones of the earth-rockfill

dams, is generally volcanic (pillow lava, basalt), i.e. originally magma erupted from a volcano. Conversely, the material in the core of the earth-rockfill dams is generally moraine of low permeability ($\sim 10^{-7}$ to 10^{-8} m/s). Moraine is a glacially formed accumulation of unconsolidated glacial debris. Thus the Icelandic earth-and rockfill dams are built of material formed through the forces of ice and fire. The settings relating to these forces additionally have to be considered in the design of the dams and appurtenant structures.

3 COMPLICATIONS, CRITERIA AND/OR MEASURES RELATING TO GEOLOGICAL SETTINGS

Iceland straddles the Mid-Atlantic Ridge which marks the boundary of the North-American Plate (NAP) and the Eurasian Plate (EP). See Fig.7. These plates move continuously apart, resulting in intrusion of magma on the boundary which again leads to tectonic activity.

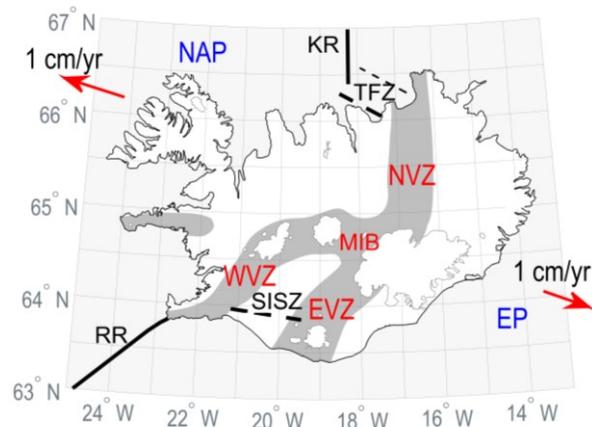


Figure 7 Volcanic zones of Iceland (grey) and tectonic settings. KR and RR are on the Mid-Atlantic Ridge. KR Kolbeinsey Ridge, RR Reykjanes Ridge, WVZ West Volcanic Zone, MIB Mid-Iceland Belt, EVZ East Volcanic Zone, NVZ North Volcanic Zone, TFZ Tjörn Fracture Zone, SISZ South Iceland Seismic Zone.

The three main volcanic zones (VZ) of Iceland follow the Mid-Atlantic Ridge. These are also called spreading zones with the NAP moving 1 cm/yr to the north west while the EP moves 1 cm/yr to the north east. On the transformation zones (Fig. 7), the TFZ

and SISZ, the largest earthquakes in Iceland originate.

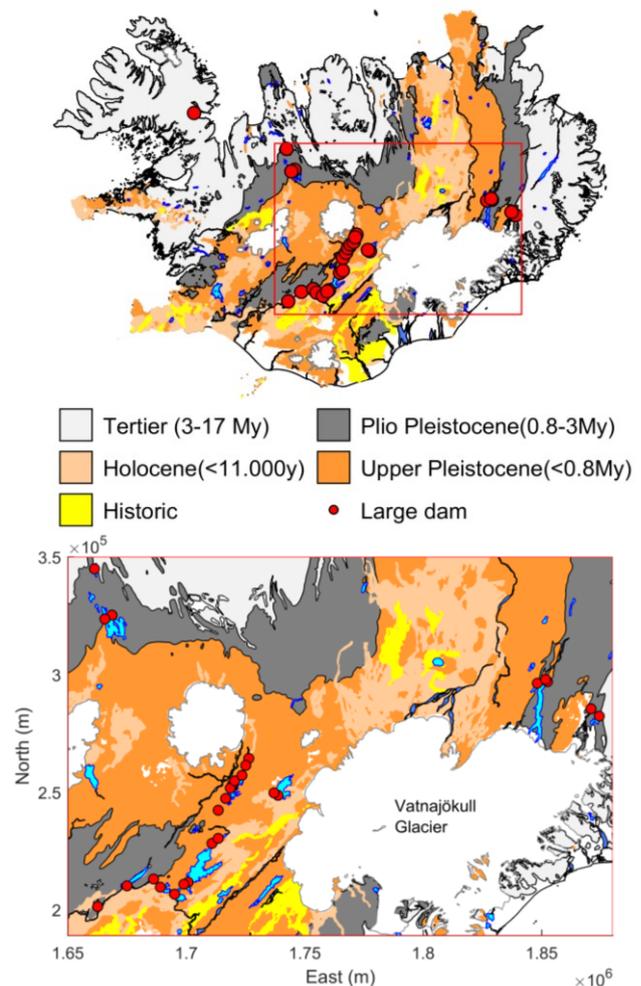


Figure 8. Bedrock geology of Iceland (*Náttúrufræðistofnun Íslands*) and the location of large dams. Bedrock is classified on the basis of its age. Postglacial lavas are divided into prehistoric (Holocene) and historic lavas (Historic- since Iceland's settlement in 874).

3.1 Geology and hydropower dams

The main features of Iceland's bedrock geology, is shown in Fig 8, classified by age. The distribution of the youngest bedrock (<0.8 My) is mostly confined to the active volcanic zones. This area is covered with hyaloclastites formed by subglacial volcanism during the Pleistocene, and partly by postglacial (Holocene) lava formations, including since after the settlement of Iceland (Historic, i.e. after 874 AD).

South- and Mid-Iceland. Many of the large dams (18 large dams of height from about 13 to 44 m) along with a number of smaller dams, are located in the Þjórsár-Tungnár

basin which lies within the volcanic zone of central Iceland (MIB and EVZ) highlands (Fig. 4 & 7). In this river system six hydropower plants (HP) have been built in steps during the last five decades. The latest one was brought online 2014, and the extension (100 MW) of the first station in this sequence (Búrfell) is ongoing. Additionally, three potential hydropower projects (total of 255 MW) in the lower region of the Þjórsá river are under consideration.

Holocene formations characterize the Þjórsár-Tungnár basin (Fig.8), constituting the Holocene Tungnaá lava flows of which the Great Þjórsá lava is the oldest, 8600 years, and Veiðivötn lava the youngest or 500 years old (Hjartarson, 2003). These are basaltic pillow lava originating from fissure eruptions (see Fig.10) within the Bárðarbunga-Veiðivötn volcanic system (Halldórsson et al. ,2008). A zone of highly permeable scoria usually exists at both the base and the surface of each lavaflow. These are commonly separated by sedimentary interbeds, comprising sand, volcanic ash and loess (Pálmason, 2016). Additionally, the lavas are highly porous allowing infiltration of precipitation into groundwater aquifers (Johannesson et al, 2007).

The lava flows and the foundation conditions have directly influenced the dam design in the area and measures taken to limit groundwater flow and seepage through the dam foundation. Pálmason (2016) describes in some detail the measures taken at each dam site. In this paper these measures are summarized and related to the overall geological conditions and formations in the area (see Fig. 8), the same principles have been used for earth-rockfill dams in other parts of the country, and are as follows:

- (1) In the older formations (Upper Pleistocene) consolidation grouting of the dam foundation is generally sufficient. Usually the grouting is conducted on three rows. A relatively deep cement grout curtain is provided on the middle row, typically 10-20 m deep, adjoined by consolidation grouting, 3-10 m, deep on each side.
- (2) In the Holocene formations (including historical formation since after the settlement

of Iceland in 874 AD) trenches are typically excavated, preferably down to a more sound and less porous lava. The trenches are then refilled as may apply with fine grained alluvial gravel, moraine, a moraine-bentonite slurry mixture or similar. The trenches are typically located in the foundation of the dam core (Fig. 6) or, if outside of this, generally connected to the core with an impervious blanket. In the core trenches filter fabrics or other filters, are normally provided prior to placing the refill.

These measures have resulted in decreased groundwater flow in the foundation. Furthermore, self-sealing of the foundation by suspended sediments of the glacial rivers has also lead to decreased groundwater flow. Generally, at the design stage, the self-sealing has been roughly estimated to reduce the flow by as much as 50% over the first decade of operation (Pálmason, 2016).



Figure 9. The Háslón Reservoir and dams.

East-Iceland. While most of the large dams are in South-and Mid Iceland, the two highest dams in Iceland are located in East Iceland, on the east border of the NVZ (Fig. 4 ,7 and 8). These are the Kárahnjúkar CFRD (198 m) (K dam) and the Desjarár dam (69 m) (D dam). The K and D dams are in the catchment area of the glacial river Jökulsá á Brú originating from under Vatnajökull Glacier, and retain the Háslón Reservoir (2600 GI) along with Sauðárdalur dam (S dam) (29 m high). See Fig. 9. Additionally three large earth-rockfill dams (15-32 m high) are further east in the catchment of another glacial river, also originating from the Vatnajökull glacier. These dams altogether provide storages for the 690 MW Fljótsdalur Station (of the Kárahnjúkar hydropower project).

The S dam is founded on soil layers. The other dams are founded on basalt and/or pillow lava of the Plio or Upper Pleistocene formations. The foundation conditions can vary markedly along the length of the dams, from relatively sound basalt to pillow lava. Additionally, the foundations of the D dam and the K dam are crossed with lineaments and faults. Mitigation measures and the foundation conditions are described in papers presented at NGM 2008 (Pálmason & Sigtryggsdóttir, 2008; Stefánsson & Kröyer, 2008; Skúlason, 2008). For the D dam the combined dam and foundation design is based on the same principles described above, i.e. with a core trench and underlying grout curtain through the more pervious lava layers (pillow lava) in the dam foundation, and grout curtain underlying the core on a basalt foundation.

North-West Iceland. Three large earth-rockfill dams (26 to 44 m high) are located in North-West Iceland (Fig. 4), in the basin of the rivers Blanda River originating partly in the Hofsjökull Glacier area and Kolkukvísl River, harnessed in the Blanda Power Station (150 MW). These dams are founded on Plio Pleistocene basalt, or on both basalt and sandstone. Trenches were generally excavated into the sandstone, but foundation measures in basalt foundation followed largely these described above for dams founded on the Pleistocene Formations.

Vestfirðir Peninsula. One large earth-rockfill dam, Þverárdam of 20 m height, is located in the Vestfirðir Peninsula. This dam forms the storage for a small hydro (2.3 MW). The dam is founded on Tertiary basalt formations. Foundation measures largely followed these described above for dams founded on the Pleistocene Formations, however with grouting on two rows. Additional measures were required where a fault crosses the foundation, comprising placing gravel over some length of the fault upstream, aiming at reduced leakage by lengthening the leakage pathway.

3.2 Glaciovolcanism and jökulhlaups

The large dams discussed above are located within and on the border of the volcanic zones. Large dams, hydropower stations, and

the volcanic systems are presented in Fig. 10a. A volcanic system consists of a central volcano, a fissure swarms or both. A central volcano is a deep-seated magma reservoir and the focal point of eruptive activity, while the fissure swarm present a shallower crustal magma chamber (see Fig. 10b,c) (Thordarson and Larsen, 2007).

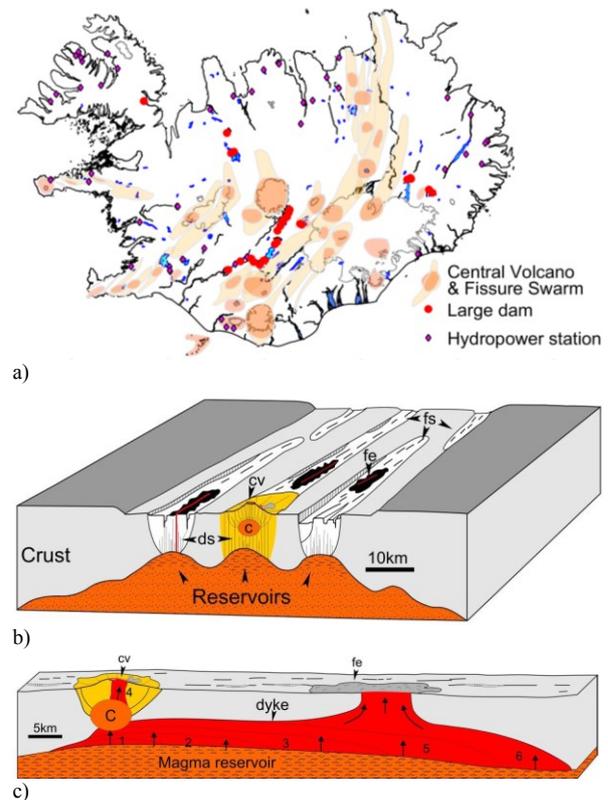


Figure 10. (a) Large dams, hydropower stations and the distribution of active volcanic systems in Iceland. (Landinformation on volcanic systems: FUTUREVOLC). (b) The main structural elements of a volcanic system. Abbreviations: c, crustal magma chamber, ds, dyke swarm, cv, central volcano, fs, fissure swarm, fe, fissure eruption. (c) Injection and growth of a dyke feeding an eruption during a rifting episode. (fig b and c: Thordarson and Larsen, 2007)

The large dams, within or in the vicinity of the volcanic zones, retain glacial rivers fed by the nearby glaciers. All of the glaciers overlay one or more central volcano and fissure swarms. In Vatnajökull five subglacial volcanic systems have been identified. Recent eruptions, include Grímsvötn central volcano in 2011, 2004, 1998 and a fissure swarm eruption in 1996 at Gjalp (Fig. 11) midway between Grímsvötn and Bárðarbunga central volcanoes. (See Fig.

13). The 1996 eruption has been influential in defining catastrophic flood events for the design of Icelandic dams as later explained. Subglacial lakes created by subglacial eruptions, and/or, above geothermal systems, may cause jökulhlaup (glacial outburst flood) For example, injection of magma to shallow depths (see Fig.10) may bring heat up to the glacier above, continuously melting the ice and creating a subglacial lake that breaks out in jökulhlaups as the basal water pressure increases enough to lift the overlying glacier (Björnsson, 2002). In Iceland several subglacial lakes are known to exist, six such in Vatnajökull. The location of these can usually be identified from depressions in the glacier surface (see Fig.12). One such subglacial lake is Grímsvötn, associated with the central volcano Grímsvötn. Grímsvötn Lake's water level generally rises due to melting of the ice by geothermal action (see Fig.12), resulting in regular drainage of the subglacial lake usually with a period of about 10 years or less. However, the extraordinary jökulhlaups from Grímsvötn in 1996 was associated with subglacial fissure eruption in Gjálp. (Björnsson, 2002). The jökulhlaup occurred in November 1996. This was preceded and indirectly triggered by the Gjálp eruption in October 1996. Meltwater due to the eruption flowed from the eruption site to Grímsvötn subglacial lake, accumulated for a month until it drained in the catastrophic jökulhlaup. During the first four days of eruption, meltwater was created at a rate of 5000-7000 m³/s. (Gudmundsson et al, 1997; Björnsson,2002).

Dams, fuse plugs and jökulhlaups. The jökulhlaups may pose a threat to dams and other infrastructures. Fig 13 shows areas inundated by Holocene jökulhlaups attributed to volcanic and geothermal activity. The inundated areas include the Þjórsár-Tungnár basin in Mid-and South Iceland were many of the large dams and associated storages and hydropower stations are located (Fig.4). In design criteria for dams located on waterways susceptible to such occurrences, the jökulhlaups are considered catastrophic flood events. The general criterion set for the relevant dams is that this should not breach

during the assigned catastrophic event, although limited damage may be expected.



Figure 11. Gjálp subglacial eruption (Oct 1996) (See the airplane for scale). (Oddur Sigurðsson)

Accommodating this a fuse plug is commonly included in a dam or on a reservoir. This comprises, a dam section with a lower crest than the other dams retaining the particular reservoir. In the relevant flood event overtopping will thus first occur on the fuse plug, initiating erosion and subsequent breaching of this. The fuse plug is thus designed to divert the flood to the downstream of the pertinent dam and ensure that overtopping and breaching will not occur on the main dams. (Pálmason & Sigtryggisdóttir, 2008; Pálmason, 2016). However, there is a great uncertainty in the definition of the catastrophic event. The approach taken has been to look to the extraordinary jökulhlaup event of 1996. For example, the design criteria for the three dams retaining the Háslón Reservoir in East Iceland considered the rate of ice melting in the 1996 event. The general criteria deduced from this has been to design the fuse plug to pass an outburst flood of 6000 m³/s lasting four days (Pálmason & Sigtryggisdóttir, 2008). Most of the dams in the Þjórsár-Tungnár basin in Mid and South Iceland are designed before 1996, and thus although jökulhlaups are considered in the design of these by incorporating a fuse plug, this particular criterion relating to the 1996 event was not used for all of the dams in this area. Assessment of the magnitude of jökulhlaup

in the relevant area should be considered. Recent volcanic activities in the nearby Bárðarbunga volcanic system urged reassessment of relevant mitigation measures in the Þjórsár-Tungnár basin.

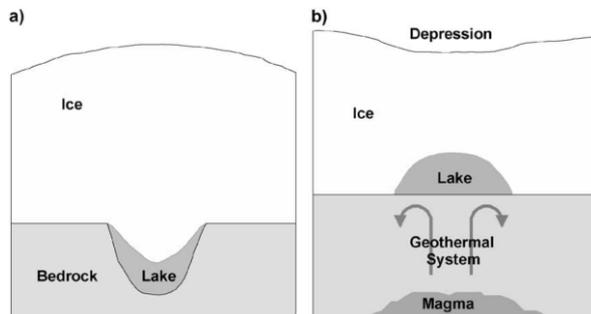


Figure 12. Schematic drawing of a) a stable subglacial lake, b) an unstable subglacial lake that drains in jökulhlaup (Björnsson, 2002).

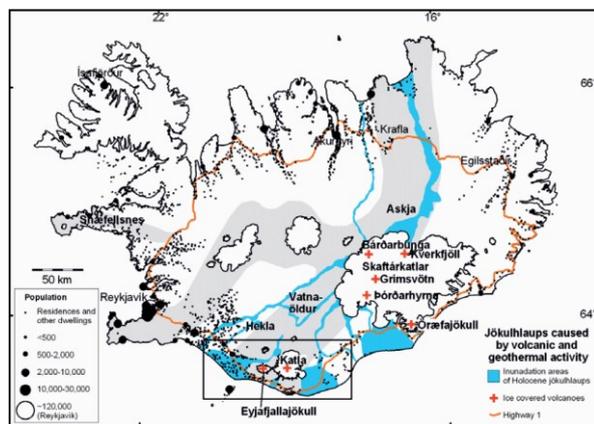


Figure 13. Areas affected by jökulhlaups attributed to volcanic activity in Iceland during the Holocene. (Volcanic zones gray shaded) (Gudmundsson et al., 2008).

3.3 Iceland's thin crust

The Icelandic crust is relatively thin (10-46 km). 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. Deformations close to Vatnajökull ice cap have a peak-to-peak seasonal displacement of ~16 mm. The thin crust was a consideration for the impounding of the 57 km² Háslón Reservoir in East Iceland (Sigtryggisdóttir et al., 2013). The effect of the reservoir on crustal movements was estimated prior to the inundation. Measured settlement after the first impounding suggested an average measured

subsidence of (14±10) mm due to the reservoir filling (Ófeigsson et al 2008).

4 TECTONIC SETTINGS AND SEISMIC DESIGN CRITERIA

The largest earthquakes in Iceland occur on transform faults and fracture zones in South and North Iceland (see SISZ and TFZ on Fig. 7). Conversely, the earthquakes originating on the spreading zones/volcanic zones are relatively small. This can be observed from the earthquake hazard map of Iceland in Fig. 14, presenting horizontal peak ground acceleration (PGA) with a mean return period of 475 years. Location of hydropower stations and large dams in Iceland are plotted on the hazard map (Fig. 14) along with the location of central volcanoes.

Iceland's major earthquake faults thus lie within the fracture zones. However, in general the Icelandic bedrock is crossed with lineaments and faults, although these may not be active in generating earthquakes.

4.1 Lineaments and active faults

Faults with movement in Holocene time (last 11.000 years) are by ICOLD definition (ICOLD, 1998) characterized as active and thus capable of generating earthquakes. In general, faults and lineaments passing through a dam foundation are examples of serious deficiencies. Faults have been encountered in the foundation of some of the large dams and/or in the vicinity of these. Furthermore, such features are a major concern for proposed dams within the SISZ, where the possibility of fault movement and opening of faults in earthquakes has to be considered.

In the case of the Háslón Reservoir in East Iceland, active faults by ICOLD definition were encountered in the foundation of the K and D dam, as well as within the reservoir area. This information resulted in foundation measures considering possible fault movement, as well as re-evaluation of the earthquake action in the area. (Sigtryggisdóttir et al, 2012; Sigtryggisdóttir et al., 2013).

4.2 Selecting seismic parameters

The hazard map on Fig. 14 indicates that the large dams in Mid, East and North-West Iceland (see Fig. 4), are located in a low seismic hazard area with a PGA of only 0.1g or less for a mean return period of 475 years. Conversely, dams and hydropower stations in the South (close to or within the SISZ) or in the North (the TFZ (see Fig.7)) are in an area of high seismic hazard with a PGA of 0.5g. The PGA values of Fig. 14 have a mean return period of 475 years. However, in the design of large dams, ICOLD (1989) recommends consideration of the Maximum Credible Earthquake (MCE). The MCE is defined as the largest conceivable earthquake that appears physically possible along a geographically defined tectonic province. The MCE is thus based on geological evidence and little regard is given to probability of occurrence.

The approach recommended by ICOLD was adopted for the dams in East Iceland retaining the Hálslón Reservoir. The assessment of the earthquake action focused on near-field events, considering the latest information on faults and overall relevant geology. Credible earthquake scenarios were defined resulting in predicted maximum PGA of 0.3, compared to the PGA of 0.1g for the 475 year event. (Sigtryggsson et al, 2012).

4.3 Seismic Analysis

Dynamic analysis of an earth dam preferably requires knowledge of the dynamic properties of the dam fill material. The maximum shear modulus has been measured for some Icelandic soils. However, neither modulus reduction behaviour of these nor damping variation has been studied. In the absence of this information, estimates based on available such from relevant literature has been used in recent analysis, and sensitivity to the selection of this investigated.

The seismic analysis of the most recent and largest Icelandic earth-rockfill dams has included both pseudo-static and dynamic analyses. This has e.g. considered the dam model response to the design earthquake motions and permanent displacement along specified slip surfaces. The pseudostatic

analysis is then considered as an index of the seismic resistance further established by the dynamic analysis. Liquefaction potential has also been investigated where relevant. Sigtryggsson et al (2012) describe the dynamic analysis of the D dam, which involved the use of two of GeoSlope's products one for the dynamic analysis of the dam subjected to the earthquake shaking and other for the stability of the dam slope and permanent deformation. The calculated permanent deformation along the selected slopes were compared to the deformation criteria for the crest/slope displacement.

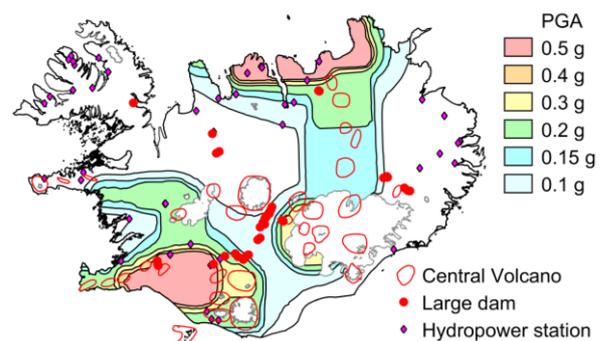


Figure 14. Location of large dams and hydropower stations in Iceland, along with central volcanoes (FUTUREVOLC), plotted on an earthquake hazard map for Iceland (ÍST EN 1998:2004/NA2010) presenting horizontal reference acceleration (PGA) for earthquakes, with a mean return period of 475 years.

5 FINAL REMARKS

A general overview of large dams in Iceland is presented in this paper. Information on small dams in Iceland are incomplete and a listing of these is required. Furthermore, information on the large dams need to be updated. As for the older large dams, update of the earthquake action with a definition of MCE and subsequent reevaluation of the dams should be considered. Furthermore, a study on geodynamic properties of Icelandic soils would indeed support earthquake analysis and design of Icelandic dams and other geostructures. Additionally, geohazards such as jökulhlaup need to be assessed more systematically than hitherto for dam design applications, and with due consideration to consequences and possible mitigation measures. In this respect, monitoring of the

respective dams, with structural health assessments as well as monitoring the geohazards that pose threat to these, is a mitigation measure that enhances safety (see Sigtryggisdóttir, 2015; Sigtryggisdóttir et al, 2015a,b). It is the author's opinion that this in general requires further attention and interest by dam owners in Iceland, particularly during dam operation. The enforcement of national regulations on dam safety may be required to boost such interest, as well as to ensure minimum design requirements. Large dams in Iceland may not be many, but their setting is challenging and have resulted in interesting dam designs. Both of which are worth studying further.

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- Landinformation and digital data to produced some of the figures were obtained from:
Landmælingar Íslands (www.lmi.is) fig 3,4,8,10a,14)
FUTUREVOLC (<http://futurevolc.hi.is>), (fig10a,14)
Náttúrufræðistofnun Íslands (www.ni.is). (fig 8)
Orkustofnun (www.os.is), (fig. 1-3) and
Hagstofa Íslands (www.hagstofa.is) (fig.1).
- Information on the contribution of individuals, e.g. on geology, is provided on the websites referred to.