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Design of fuse plugs in earth-rockfill dams in Iceland

La conception des dispositifs fusibles intégrés dans les barrages en remblai en Islande

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ABSTRACT: Volcanic eruptions are common in Iceland, along with associated hazards such as jökulhlaups (glacial outburst floods) triggered by subglacial eruptions, geothermal activity, or the breaching of natural dams at the glacier margin. The majority of jökulhlaups in Iceland stem from the 8200 km^2 glacier Vatnajökull. Dams in Iceland are generally designed to withstand runoff floods from their watershed. However, for dams in catchments fed by the Vatnajökull glacier, events such as jökulhlaups may vastly exceed the design floods and cause severe damage to the pertinent structures. In this context, fuse plugs have been incorporated into the dam structures at favourable locations to control the damage during such floods. This paper provides an overview of design principles of fuse plugs in earth-rockfill dams in Iceland, as well as on the underlying hazards requiring such measures. All the fuse plugs discussed are owned and operated by Landsvirkjun, the National Power Company of Iceland.

RÉSUMÉ: Les éruptions volcaniques sont courantes en Islande, de même que les risques naturels qui leur sont associés tels que les « jökulhlaup » (inondations glaciaires). Ces derniers phénomènes sont déclenchés soit par des éruptions sous-glaciaires ou du fait d’une activité géothermique sous-glaciaire ou encore suite à la rupture d’un barrage de glace en bordure de glacier. La majorité des « jökulhlaup » en Islande proviennent du glacier Vatnajökull, d'une superficie de 8 200 km^2.Les barrages en Islande sont conçus pour résister aux inondations provenant du bassin versant. Toutefois, dans le cas des barrages situés dans les bassins versants alimentés par le glacier Vatnajökull, des événements tels que « jökulhlaup » peuvent dépasser les crues pour lesquelles les barrages sont conçus et causer de graves dommages aux structures concernées. Dans ce contexte, un dispositif fusible a été incorporé dans la structure du barrage à un emplacement favorable pour limiter les dommages qui pourraient être subis par les barrages lors de telles inondations. Ce document donne un aperçu de la conception des dispositifs fusibles intégrés dans les barrages en remblai en Islande, ainsi que des risques qui sous-tendent à la mise en place de telles mesures.

Keywords: Fuse plug; jökulhlaup; earth-rockfill dam; subglacial eruption; dam breach.

1 INTRODUCTION

Volcanic eruptions are common in Iceland with such events occurring on average at 3–4 year intervals. The most frequent associated volcanic hazard is jökulhlaup (glacial outburst flood) triggered by subglacial eruptions or geothermal activity. The majority of jökulhlaups in Iceland originate from the 8200 km^2 glacier Vatnajökull (see Figures 1 and 2). The glacier straddles Iceland´s Eastern Volcanic zone, with seven central volcanoes, see Figure 1.

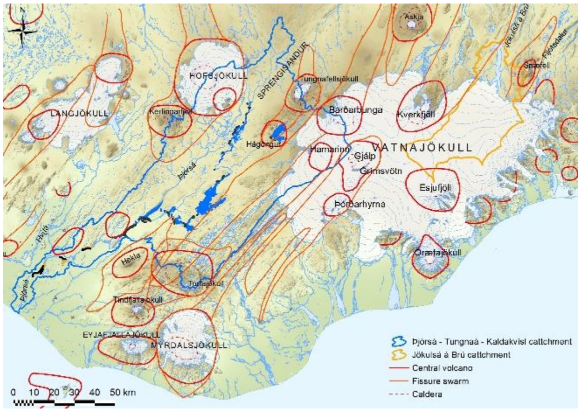

Figure 1. South and mid-Iceland: Central volcanoes and related fissure swarms and calderas.Catchment area for the Þjórsá-Tungnaá and the Jökulsá á Brú watersheds are respectively shown with blue and yellow lines.

Jökulhlaups pose threats to dams and related structures within catchments fed by Vatnajökull (see e.g. Sigtryggsdottir, 2016). The Bárðarbunga volcanic system is shown on Figure 1. Eruptions on the subglacial part of the system have caused jökulhlaups mostly to the north into the rivers Jökulsá á Fjöllum (mainly) and Skjálfandafljót (less frequent), but also to the southwest into the watersheds of the rivers Kaldakvísl, Sylgja and Tungnaá (see Figure 3). Eruptions on the system occur on average twice a century. Active periods have been identified, e.g. in the 15th century and in the 17th century, with altogether 10 identified eruptions. Approximately 90% of the eruptions on the volcanic system are subglacial (Larsen and Gudmundsson, 2016). Figure 2 shows areas affected by jökulhlaups attributed to volcanic activity in Iceland during the Holocene (last 10 000 years).

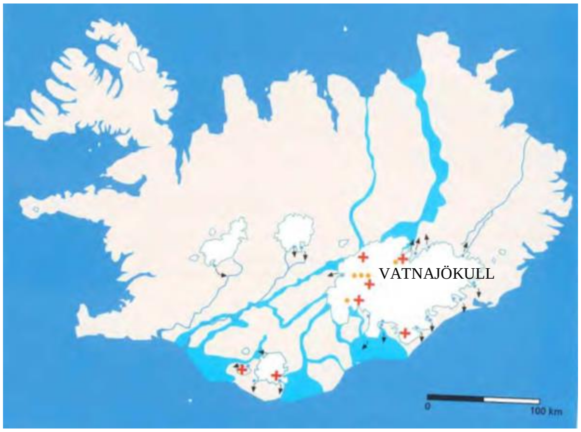

Figure 2. Areas affected by jökulhlaups attributed to volcanic activity in Iceland during the Holocene, shown in blue. Red crosses: volcanoes; yellow dots: geothermal spots; blue spots: glacial lagoons, arrows: directions of jökulhlaups (Björnsson, 2009).

A large uncertainty is associated with estimates of both size and probability of occurences of jökulhlaups. However, it is acknowledged than jökulhlaups may markedly exceed the design floods for dams and cause severe damage to the pertinent structures. A fuse plug has been incorporated into many dams, as a mitigation measure to control the damage during such floods. The fuse plugs, generally comprise a dam section with a lower crest than other dams on the same reservoir, ensuring that overtopping will only occur on the fuse plug.

Locations of fuse plugs in dams in Iceland are detailed in Figure 3. Currently, altogether eight fuse plugs have been constructed in the catchment of the glacial rivers Þjórsá, Tungnaá, and one in the catchment of the river Jökulsá á Brú (see Figure 3). This paper provides an overview of these fuse plugs in earthfill dams, the pertinent design consideration, as well as the underlying hazards calling for such measures. All the fuse plugs discussed herein are owned and operated by Landsvirkjun, the National Power Company of Iceland.

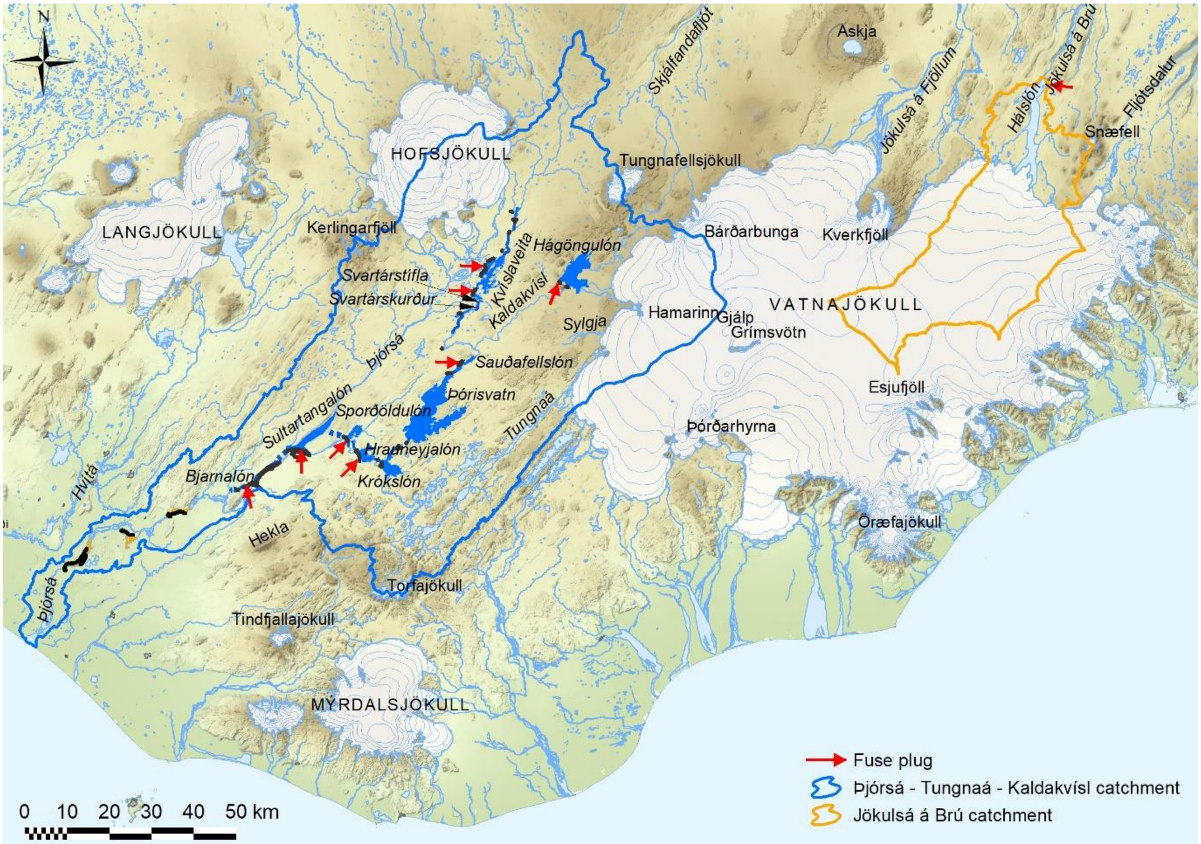

Figure 3. Fuse plugs in Iceland. a) Fuse plugs (8) on the catchment of the Þjórsá-Tungnaá-Kaldakvísl (blue), b) Fuse plug (1) on the catchment of the Jökulsá á Brú (yellow).

2 DESIGN CRITERIA AND ASPECTS

2.1 Design floods - Runoff floods

Recent dams in the catchment of the Þjórsá-Tungnaá, are designed to withstand runoff floods from the watershed with a 1000 year return period, Q_{1000}, with estimated discharge ranging from 1000 to 4000 m^3/s. The structures are also designed to withstand larger runoff floods, with a discharge of 1.5 Q_{1000}, or so-called probable maximum floods (*PMF*), yet allowing limited damage. Such discharge estimates range from 2500 to 7500 m^3/s, from the highest lying reservoir to the lowest within the watershed. Other types of events are also considered, e.g. breaching of a fuse plug higher on the watershed. In case of possible floods larger than the design floods (1.5 Q_{1000} or *PMF*), a fuse plug, with a higher capacity, should be incorporated into the structures.

2.2 Jökulhlaups

Hydraulic design criteria for the fuse plugs in Figure 3 has changed markedly over the years. Observations of meltwater production during the 13 day subglacial fissure eruption of Gjálp, on the Bárðarbunga volcanic system in 1996, have, in recent years, been used to determine design events for dimensioning of fuse plugs (see Figure 3). The eruption took place on a 6000 m long fissure, where the thickness of the glacier was 550–750 m (Gudmundsson et al., 1997). It is estimated that 2500–3000•10^6 m^3 of water melted during the eruption. The meltwater flowed from the fissure to a subglacial lake, Grímsvötn, accumulated for a month until it drained in a large jökulhlaup to the south. The peak discharge in the jökulhlaup was an order of magnitude larger than the peak discharge generated during the eruption (40 000–50 000 m^3/s with 3600•10^6 m^3 total volume). Water melted at an average rate of 5000 m^3/s during the first four days of the Gjálp eruption), with a short peak of about 8000 m^3/s at the start of the eruption (Gudmundsson et al., 1997; Gudmundsson et al., 2004; Björnsson, 2002).

The melting rates during the Gjálp eruption may be used to calculate discharge during similar subglacial fissure eruptions. Important input parameters include fissure length, fissure orientation and glacier thickness, see e.g. Guðmundsson (2014). Probability (or return periods) of jökulhlaups of different sizes may thus be linked to eruption frequency in Iceland (Guðmundsson, 2014). The smaller jökulhlaups with a discharge less than 1000 m^3/s are most likely, while catastrophic floods with discharge exceeding 100 000 m^3/s are possible, but unlikely. Such events could potentially occur as a result of an explosive eruption within the Bárðarbunga caldera. Jökulhlaups to the southwest from Vatnajökull, with a discharge of 3 000 to 15 000 m^3/s, may have occurred a few times during the Holocene (Larsen and Gudmundsson, 2016; Verkís, 2014; Larsen et al., 2013; Þórarinsson, 1974; Freysteinsson, 1972) and can be compared to the run-off *PMF* discussed in § 2.1.

The earlier dam design, comprising most of the dams in the Þjórsá-Tungnaá basin, is based on jökulhlaups larger than the probable maximum runoff floods, but the size is not based on information gathered during the Gjálp eruption.

2.3 Design aspects

A fuse plug comprises a dam or a dam section with a lower crest than other dams retaining each particular reservoir. In the relevant flood event overtopping will thus first occur on the fuse plug, initiating marked erosion and subsequent breaching. The breached section must accommodate the passing of the flood, otherwise this will probably expand.

In recent years, fuse plug design in Iceland has been based on various research of embankment breaching, available at the time of design. This includes empirical equations by D.C. Froehlich, see e.g. Froehlich (2008), for evaluation of the average width of a breached section and the corresponding erosion time. Furthermore, the selection of fill material must consider enhancing the progression of the initital erosion to a full breach. In the latest design additional measures have been taken to control location of initial erosion, e.g. by installing pilot channels.

In the case that a fuse plug adjoins the main dam, the lateral extent of the breaching should be limited by some measure, preferably a reinforced concrete wall. However, in the case that a retaining wall cannot be accommodated, the effectiveness of reinforcing the margin between the main dam and the fuse plug with large rocks can be considered. In this, potential limits to the extension of a breached section should be considered. Finally, the flow has to be bypassed safely in a channel or by robust divertion dikes, downstream of the dam.

3 FUSE PLUGS IN ICELAND

Fuse plugs are incorporated into most major dams on reservoirs fed by glacial rivers in Iceland. Eight fuse plugs have been constructed in the Þjórsá-Tungnaá catchment, and one in the Jökulsá á Brú catchment (see Figure 3). Additionally, fuse plugs are planned in relation with three hydropower stations proposed in the lower part of the Þjórsá river. Fuse plugs in the catchment of the Þjórsá-Tungnaá are installed on dams in the following reservoirs operated by Landsvirkjun (from the highest lying to the lowest): Hágöngulón, Kvíslaveita, Þórisvatn-Sauðafellslón, Hrauneyjalón, Sultartangalón, and Bjarnalón. HEPs on the system have a combined energy capacity of 1035 MW. Verkís Ltd (previously Verkfræðistofa Sigurðar Thoroddsen, VST) is the designer of all the fuse plugs in this area, except for the one on the Bjarnalón. In East-Iceland, one fuse plug (designed by Verkís) is installed on the Hálslón reservoir (Figure 3 and 4) fed by the Jökulsá á Brú. Discharge from this reservoir is diverted to the 690 MW Fljótsdalur HEP through a 40 km tunnel system.

The following provides a short overview of these fuse plugs. The discussion will follow the timeline of design and construction of the relevant reservoirs and associated fuse plugs.

3.1 Bjarnalón reservoir 1966-69

Low earth-rockfill dams, designed by US Engineering firm Harza, on the Bjarnalón reservoir, may serve as fuse plugs in extreme flooding and can be considered the first fuse plug constructed in Iceland. However, it is unclear whether this was the original intention.

3.2 Sauðafellslón reservoir 1970

The first structure in Iceland to be designed as a fuse plug was constructed around 1970 in relation with the development of Lake Þórisvatn as a reservoir for hydroelectric power generation. The fuse plug is on the Sauðafellslón, a small reservoir upstream of Lake Þórisvatn. The fuse plug has a central core of moraine, abutted with filters and course rockfill, protected with riprap on the upstream slope and the crest. In the design of this first fuse plug the focus was on providing a lower dam section that would be overtopped before the main dam. The design did not fully consider fill material enhancing erosion initiation and progression to a full breach. Hence, for the current fuse plug the erosion and breaching may take longer time than desired.

3.3 Hrauneyjalón reservoir 1979

The second fuse plug was built around 1979, on the main dam on the Hrauneyjalón reservoir. The fuse plug is incorporated in the south end of the dam, where the dam crest is the lowest. The fuse plug is 100 m long, separated from the main dam by a concrete retaining wall. Furthermore, the fuse plug crest is 1 m lower than the main dams. The fuse plug section is constructed in the same way and of the same material as the main dam.

3.4 Sultartangalón reservoir 1984/1996

A 400 m long fuse plug section was constructed in 1984 on the dam of the Sultartangalón reservoir. The fuse plug section is 1 m lower than the crest of the main dam, and located at the easternmost end of the main dam, west of the associated spillway. The fuse plug is of the same material as the main dam, however, the riprap on the upstream face and the crest is of smaller rock sizes. A dike comprising large riprap was installed at each fuse plug end. The dam crest was raised in 1996 and rubber gates placed on the spillway.

3.5 Kvíslaveita diversion and reservoir1980-1997

Kvíslaveita diversion, constructed in the period 1980-1997, comprises a system of dams, canals, bottom outlets and gate structures that partially control the discharge of the Þjórsá and its tributaries into Þórisvatn reservoir. Only two relatively short fuse plugs were originally installed on this system, along with a fuse plug canal (Svartárskurður in Figure 3). The canal is about 100 m wide and a 1 m high. A reassessment of the size of potential jökulhlaups, during volcanic activity on the Bárðarbunga volcanic system in 2014, led to the design and construction of a new fuse plug on the dam Svartárstífla in 2015, as discussed in § 3.8.2.

3.6 Hágöngulón reservoir 1997 to 1999

The Hágöngulón reservoir, constructed in 1997–1999, is the highest lying man made reservoir in Iceland with the spillway crest at 816 m a.s.l. Two dams create the reservoir, the 26 m high main dam and the 15 m high saddledam. The saddledam is approximately 500 m long, with a 100 m long fuse plug constructed at its easternmost end. The fuse plug crest is one meter lower than the crest of both the remainder of the saddledam, and of the main dam. Geothechnical design aspects of the fuse plug were mostly the same as those of the main dam. The 2014 reassessment of potential jökulhlaups into Hágöngulón reservoir, instigated a review of the design of the fuse plug in 2015, as discussed in § 3.8.1.

3.7 Hálslón reservoir 2006

The impounding of the Hálslón reservoir started in September 2006, with the full supply level reached a year later. Water in the reservoir is retained by three large dams, the main dam is 200 m high and the saddledams are about 70 and 25 m high. A spillway is located on the westernmost end of the main dam, while a 100 m long fuse plug is on the 70 m high saddledam (Figure 4). The fuse plug design considers a jökulhlaup from the Vatnajökull glacier. The design discharge estimates for the capacity of the fuse plug are based on assessments from the 1996 Gjálp eruption. The general criteria deduced was to design the fuse plug to pass a 6000 m^3/s flood. The return period of such a flood was not estimated.

The crest of the fuse plug section is 1 m lower than the remainder of the dam. In order to enhanche breaching, in case of overtopping, the fuse plug contains almost entirely cohesionless fills. A retaining wall separates the main dam and the fuse plug. About 600 m long canal extends from the fuse plug down to the adjoining valley depression to facilitate efficient passing of the floodwater through the breached section, preventing it from flowing along the downstream damtoe of the main dam. (Pálmason and Sigtryggsdóttir, 2008).

Figure 4. The Hálslón reservoir, dams, spillway and fuse plug (Sigtryggsdottir et al., 2016). Photo: Emil Thor.

This fuse plug marks a milestone in the developement of the hydraulic design criteria and geotechnical aspects for such structures in Iceland. Firstly, regarding required discharge capacity. Secondly, in a careful selection of materials that enhance erosion. Furthermore, a robust downstream canal for diverting the flood away from the main dam is provided. However, the design is somewhat compromised in that a road with asphalt pavement lies along the fuse plug crest. The asphalt pavement may delay the initiation of erosion and thus the time for reaching a fully breached section.

3.8 Review in 2014-2015

An asessment of fuse plugs in the catchment of the Þjórsá-Tungnaá rivers was initiated in 2014 due to volcanic activity on the Bárðarbunga fissure swarm. Subglacial eruptions on this fissure swarm may result in jökulhlaups into the Hágöngulón reservoir, and subsequently into Kvíslaveita reservoir, thus a fuse plug is an important safety measure on these reservoirs to limit flooding hazard.

The assessment resulted in the construction of additional structures to safely bypass a potential flood with a maximum discharge of 6000 m^3/s, on the breached fuse plug, at the Hágöngulón reservoir. A new fuse plug was added on the Svartárstífla dam, a part of the Kvíslaveita diversion. The capacity of the fuse plug is 2200 m^3/s. The review was based on meltwater generation during the 1996 Gjálp eruption, see §2.2. Dam design aspects of the added measures are discussed in §3.8.1 and §3.8.2.

3.8.1 Hágöngulón reservoir

The fuse plug design review in 2014, resulted in the construction of rockfill dikes, extending 90 m downstream and 70 m upstream from the saddledam, intercepting where the dam meets the fuse plug (Figure 5). The slopes of the downstream dike are protected with riprap, 0.9 to 1.2 m in diameter, strengthened with a robust reinforcement mesh anchored into the dike. The slopes of the upstream dike are protected with riprap stones, 1.5 to 2 m in diameter, however similarly strengthened, but in this case with corrosion resistant reinforcement. The purpose of these dikes is to protect the saddledam in case of flooding through the breached fuse plug.

3.8.2 Kvíslaveita reservoir, Svartárstífla dam

In the design of the fuse plug protecting Svartárstífla dam, similar design principles for the selection of material were followed as for the fuse plug on the Hálslón reservoir. Also incorporated into the design was the rise of the water level to approximately 0.5 m over the fuse plug crest for markedly initiating a breach. In order to further enhance breaching, a short section of the fuse plug was constructed weaker than the rest (Figure 6). Installing a weak section is a new design feature referred to as a pilot channel. The purpose of this is to speed up the breaching process at a chosen location.

Figure 5. Fuse plug at Hágöngulón reservoir. Rock-fill dikes upstream and downstream from the saddle dam. Photo: Kristín Martha Hákonardóttir

Figure 6. Fuse plug in Svartárstífla dam. View of the pilot channel, downstream.

4 SUMMARY AND FINAL REMARKS

The design of the fuse plugs discussed above span a period from 1970 till this day. The fuse plug design principles have changed over this time period, with the advancement of related knowledge, as well as increased general awareness on safety. The earliest designs considered only a fuse plug with a crest elevated 1 m lower than this of the main dams. While, today’s design additionally considers selecting material for enhancing erosion and installing pilot channels for controlling the breach. Furthermore, the design critieria regarding the size of the jökulhlaups considered has developed as the reasearch into glaciovolcanism has advanced.

The authors of this paper, emphasize that there are still marked uncertainties involved: Firstly regarding the jökulhlaups, size and frequency of occurrence; Secondly, regarding the empirical Froehlich breaching equations for breach width and the time factor; Thirdly, regarding the material used enhanching the erosion; Fourthly, on the throughflow capacity of the rockfill above the core; Fifthly, on the effectiveness of the pilot channels for enhancing the breaching; Sixthly, regarding the effect of frost in the fuse plug till. Finally, seventhly and eightly, the robustness of the measures installed to protect the main dam; Seventh being, retaining walls at the conjunction of the main dam and fuse plug; And, eight, confirming the assumed robustness of diversion dikes designed to protect the main dam in an extreme flood event.

Pálmason (2018) has further ideas on how the design of a fuse plug may be enhanched and the potential breaching localised, by forming a 0.5 to 1 m high ledge extending from the pilot channels. In an overtopping situation, the water flow through the channel will fall from the ledge and plunge down to the slope below. Furthermore, he has aired the idea of installing for example two fuse plugs on the same reservoir with different crest elevation.

5 REFERENCES

Björnsson, H. 2002. Subglacial lakes and jökulhlaups in Iceland. *Global and planetary change* **35,** 255–272.

Björnsson, H. 2009. *Jöklar á Íslandi (e. Glaciers in Iceland)*. Bókaútgáfan Opna. Reykjavík, Iceland.

Froehlich, D.C. 2008. Embankment dam breach parameters and their uncertainties. *J.of hyd. Eng.* **134,** 1708–1721.

Gudmundsson, M.T., Sigmundsson, F., Björnsson, H. 1997. Ice-Volcano interaction of 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. *Nature* **398**, 954–957.

Gudmundsson, M.T., Sigmundsson, F., Björnsson, H., Högnadóttir, Þ. 2004. The 1996 eruption at Gjálp, Vatnajökull ice cap, Iceland: Efficiency of heattransfer, ice deformation and subglacial water pressure. *Bull Volcanol*. **66**, 46–65.

Gudmundsson, M.T. 2014. *Köldukvíslarjökull – mögulegar stærðir hlaupa vegna gosa á vatnasvæði Köldukvíslarjökuls* (*e. The Kaldakvísl glacier – possible size of glacial outburst floods on the Kaldakvísl glacier catchment area*). Memo dated 2014-10-22.

Larsen, G., Gudmundsson, M.T. 2016. Bárðarbunga. *Catalogue of Icelandic Volcanoes* (Eds: Ilyinskaya, Larsen and Gudmundsson). IMO, UI, CPD-NCIP.

Larsen, G., Gudmundsson, MT., Björnsson, H., Högnadóttir, Þ. *Náttúruvá á Íslandi. Eldgos og jarðskjálftar*. Viðlagatrygging/ Háskólaútgáfan, Reykjavík, Iceland.

Palmason, PR, Sigtryggsdottir, FG. 2008. Some design aspects of the Desjararstifla dam. *NGM 2008: Proceedings, 15th Nordic geotechnical conference*, Norway.

Pálmason, P.R. 2018draft. *Design principles of fuse plugs.* Memo by Verkis. April 2018.

Sigtryggsdottir, F.G. 2016. Hydropower dams in the land of ice and fire. *NGM 2016: Proceedings 17th Nordic geothechnical conference*. Reykjavík, Iceland.

Sigtryggsdottir, F.G., Snæbjörnsson, J.Þ., Grande, L. and Sigbjörnsson, R. 2016. Interrelations in multi-source geohazard monitoring for safety manangement of infrastructure systems. *Structure & Infrastructure Eng*. **12(**3), 327–355 https://doi.org/10.1080/15732479.2015.1015147

Verkís. 2014. *Ummerki hlaups og mat á stærð þess í gömlum farvegi Köldukvíslar, sunnan Syðri-Hágöngu*. Memo no. 05126003-1-MB-0240.

Þórarinsson, S. 1974. *Vötnin stríð*. Menningarsjóður, Reykjavík.