Flood design criteria for Kárahnjúkar dam – a glacially dominated watershed

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Abstract

The Háslón reservoir is the main water storage for the Kárahnjúkar hydroelectric powerplant in eastern Iceland. Of the 1800 km² reservoir drainage basin, 1400 km² are covered by glacier, making discharge and consequently floods into the reservoir dominated by characteristics of the glacial discharge. The paper discusses the flood design criteria applied for the reservoir. Three flood events were identified; a design flood corresponding to a glacial melt event, a safety check flood (probable maximum flood (PMF)) corresponding to a probable maximum precipitation, and a catastrophic flood corresponding to a volcanic eruption under the glacier within the drainage basin. Hydraulic structures designed to pass the floods through the reservoir are described briefly, a spillway at the Kárahnjúkar dam, designed to pass the design flood and the PMF flood, and a fuse plug at the Desjarárstífla dam, designed to erode and pass the catastrophic flood.

Introduction

The Kárahnjúkar hydroelectric project, now completed in Iceland, is owned by Landsvirkjun, the National Power Company. It was constructed to supply electricity to Alcoa’s new aluminum plant on the east coast of the country. The location of the project is shown in Fig. 1.
The project harnesses two rivers mainly fed by the Vatnajökull glacier. The larger of these two, the Jökulsá á Dal river, emerges from underneath the glacier at about El. 600 m and discharges directly into the Hálslón reservoir, the project main water storage with live storage of 2100 million m$^3$ at FSL El. 625 m. The reservoir is formed by the 198 m high Kárahnjúkar dam and two lower saddle dams. From Hálslón reservoir and the Ufsarlón pond on the smaller river, the harnessed water is conveyed through a 53 km long mostly TBM bored interconnected tunnel system to the Fljótsdalur underground power station with tailwater at El. 26 m. Six 115 MW Francis turbines, operate under a gross head of up to 600 m and maximum discharge of 144 m$^3$/s with an energy production of about 5000 GWh/a. Power generation commenced in November 2007, with full production achieved in early 2008 and all construction basically completed in late 2008.

Fig. 1: The drainage basin of the Jökulsá á Dal river at Kárahnjúkar (hatched) and layout of the Kárahnjúkar Hydroelectric Project. Also shown are drainage basins for discharge gauging stations (vhm).
Hydrology of the drainage basin and flood design criteria

The river Jökulsá á Dal originates in Brúarjökull glacier which is an outlet glacier on the northeast side of Vatnajökull glacier, Europe’s largest glacier. It is the largest river in east Iceland and among the rivers in Iceland that carries the largest amount of sediment with average sediment concentration of about 3000 g/m³. The total length from the glacier to the ocean is about 150 km and the corresponding drainage basin is approximately 4000 km².

Of the 1800 km² drainage basin for the reservoir shown in Fig. 1, 1400 km² are covered by glacier, making discharge and consequently floods into the reservoir dominated by characteristics of the glacial discharge. Fig. 2 shows the statistical distribution of daily average natural flow into the reservoir as predicted from hydrological simulations over a 50 year period. The discharge has a distinct seasonal character; peaking at around 1000 m³/s on warm days during the glacial melt period from mid June to mid September and dropping to 10-20 m³/s in mid winter.

Several active volcanic areas are known to exist underneath the Vatnajökull glacier, none of those however within the drainage basin of the Hálslón reservoir. Still the possibility of volcanic activity within the reservoir drainage basin cannot be ruled out with absolute certainty.

No specific legislation or regulations apply to flood design criteria for dams in Iceland. Landsvirkjun has therefore developed their own rules, based mostly on Norwegian regulations for flood design criteria for dams, but adapted to Icelandic conditions (VST et al. 2006). In particular, these have been adapted to the possibility of drainage basins covered partly by glaciers with areas of potential volcanic activity underneath. The following three flood types are defined:

- **Design flood**: Hydraulic structures shall pass this flood without any damage and without any risk to dams or other pertinent structures.

- **Safety check flood**: Hydraulic structures shall pass this flood without risk of dam-break. Limited damage to structures is tolerated, e.g. erosion of a fuse plug.

![Fig 2: Daily average natural flow to the Hálslón reservoir and its statistical distribution within the year.](image)
• **Catastrophic flood**: This flood is due to a natural catastrophic event, such as a major volcanic eruption underneath a glacier, or unknown jökulhlíoup (glacier outburst flood). Hydraulic structures are in general not required to pass such floods, but the design shall attempt to minimize the consequences.

Dams are categorized in accordance with the consequences of dam-break and the size of the design flood and the safety check flood is chosen based on the risk category. For the highest risk category, applicable to all three dams at Kárháhnjúkar, a spillway would normally be designed to pass the design flood corresponding to a 1000 year event and a fuse plug would be designed to pass the safety check flood corresponding to the PMF flood. However, due to the importance of Hálslí reservoir for the Kárháhnjúkar HEP, its large size and potentially dangerous dam-break floods, a larger factor of safety was applied by designing the Kárháhnjúkar spillway to pass both the 1000 year flood and the PMF flood and the fuse plug to pass the catastrophic flood.

### Flood analysis and construction of flood hydrographs

Flood analysis for the Jökulsá á Dal river at the Kárháhnjúkar dam is based on continuous discharge records from two downstream gauging stations, Brú (vhm 236) and Hjarðarhagi (vhm 110), shown in Fig. 1 (KEJV, 2003). The characteristics of the drainage basins for these three locations are summarized in Table 1.

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<th>Table 1: Summary of drainage basin characteristics at Jökulsá á Dal</th>
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<td>Kárháhnjúkar dam</td>
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<td>Brú (vhm 236)</td>
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<td>Hjarðarhagi (vhm 110)</td>
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¹ According to simulated discharge 1950 to 2001

For the Kárháhnjúkar dam, 78% of the drainage basin is covered by glacier and the largest historical floods are caused by glacier melt on warm summer days. The same applies to Brú where two thirds of the drainage basin is covered by glacier, but to a much less extent to Hjarðarhagi, where less than half of the drainage basin is covered by glacier. Analysis of annual peak discharges at the two gauging stations supports this, showing all annual peaks at Brú to occur within the glacial melt period but only about half of those at Hjarðarhagi. The discharge records at Brú therefore better represent the hydrological conditions at the Kárháhnjúkar dam, but they are too short to use in statistical analysis of floods. However, analysis of simultaneously recorded floods at Brú and Hjarðarhagi during the summer period reveals only small differences in discharge, indicating that during the glacial melt period the difference in flood sizes at these two gauging stations is insignificant, especially for the larger floods. The statistical
The analysis of floods at the Kárahnjúkar dam is therefore based on data for the largest floods at Hjarðarhagi, but limited to the glacial melt period.

The Log-Pearson Type 3 distribution was used to fit the data with a skew coefficient calculated from the data series and then adjusted to yield an unbiased estimate for the skew. Fig. 3 shows the results for the instantaneous discharge, the daily mean discharge and the 5-day discharge. The hydrograph of the design flood, shown in Fig. 4, is constructed from these, but with discharges multiplied by a safety factor of 1.25 to account for the short discharge records available and the possibility of warm weather following a surge of the Brúarjökull glacier. During surges the glacier advances suddenly several kilometres and becomes thicker and heavily fractured. This occurs every 60-90 years, and is known to increase discharge temporarily. The latest surge of the Brúarjökull glacier occurred in 1964. The peak discharge of the design flood is approximately 1400 m$^3$/s. Due to damping of the flood peak when routed through the reservoir the resulting maximum outflow is 1350 m$^3$/s with a resulting maximum water level at El. 627.5 m. Here we have taken the reservoir to be full at the start of the design flood inflow, another conservative assumption.

The PMF flood into the Háslón reservoir is estimated by assuming an extreme rainfall event on frozen ground to maximize the peak discharge into the reservoir. The extreme rainfall is applied to the entire drainage basin except the glacier area above El. 1200 m which is about 63% of the glacier catchment area. Runoff of possible rain at higher elevations is expected to be delayed by the last winter snowpack on the glacier surface. A 3-hr unit hydrograph was created based on Snyder’s methods. The probable maximum precipitation (PMP) is calculated from M5 precipitation estimate for Iceland (Eliasson 1995). Event duration of 72 hours was selected which is believed to be conservative. This results in a maximum 24 hour precipitation of 341 mm and a total precipitation of 523 mm during the 72 hour period. The resulting PMF hydrograph is shown in Figure 4. The maximum inflow into the Háslón reservoir is approximately 4000 m$^3$/s. Due to damping of the flood peak when routed through the reservoir the resulting maximum outflow is 2250 m$^3$/s, with corresponding maximum water level at El 628.5 m.
An even larger flood than that estimated above could result from major volcanic eruption underneath the glacier. As there are no known active volcanoes within the catchment area, no direct data exists to assist in estimating the potential size of such floods. Experience from a major eruption at Gjálp in Vatnajökull glacier in 1996 some 20-30 km west of the Háslón drainage basin indicates continuous discharge of some 6000 m³/s from direct melting of glacial ice by the volcanic activity for several days at the height of the eruption (Gudmundsson, 1997). This estimate is used as a catastrophic flood for the Háslón reservoir.

**Spillway design**

The Kárahnjúkar spillway consists of a side canal, an upper chute, a lower chute, an aerator, a short lower platform, a plunge pool and a tailwater dam. For detailed description of each component, see Tomasson et al. (2006) and Gardarsson et al. (2009).

Environmental constraints governed the location of the spillway, requiring extensive measures in order to counteract the prevailing and in many respect difficult conditions. The spillway is designed to pass the design flood of 1350 m³/s without incidents and the safety check flood (PMF) of 2250 m³/s allowing limited damage to the structure. With respect to the downstream canyon and plunge pool, a scour design discharge of 950 m³/s (500 year event) was adapted. For larger discharges damage to the opposite canyon wall and plunge pool structures is accepted as these will in no way threaten the safety of the dam or other parts of the spillway structure.

The main design challenges for the spillway were related to the lower chute end and scour potential in the canyon. Several mitigation measures were taken. The lowest part of the chute is widened so the energy per unit area is decreased when the jet leaves the chute. A two step design was adapted for the lower chute end with an oblique edge lined up with the direction of the canyon. Furthermore, to minimize...
scour potential for the jet as it impinges into the canyon, baffles were installed at the lip of the chute to break up the jet. In addition, a tailwater dam and a plunge pool are constructed in the canyon to act as a water cushion to limit the scour potential of the falling jet and the resulting flow in the plunge pool. The effects of the air entrainment into the flow at the aerator also aids in breaking up the jet.

The Kárahnjúkar dam spillway has experienced its first two spilling periods (see Fig. 5). It performed in an expected and satisfactory manner in both instances. The flow in the side canal and the chute was as designed and observed in the laboratory models. The measures taken to minimize erosional power of the jet as it impinges into the canyon downstream of the dam seem to be successful although the tailwater dam and the plunge pool had not been constructed (Gardarsson et al. (2009)).

Fuse plug design

A fuse plug is located at the eastern end of the Desjarárstífla dam as shown in Fig. 6. The purpose of the fuse plug is to prevent the dams from being overtopped in case of inflow into the reservoir beyond the PMF. The downstream portion of the fuse plug comprises a more erodible materials than in the main dam, besides the crest elevation of the fuse plug is at El. 629.5 m, or 1.0 m lower than that of the main dam. The fuse plug is about 100 m long founded on rather solid rock that was blasted down to El. 618 m and deepened in the middle with a 30 m wide channel to El. 615 m. The channel extends about 100 m into the reservoir. Following a sharp bend a 60 m wide steep (6%) straight discharge channel is excavated in the rock down to the valley bottom away from the dam. A concrete retaining wall is provided between the main dam and the fuse plug section to protect the main dam from erosion in case of fuse plug breaching. The wall extends about 70 m beyond the dam body at the downstream side. The location of the fuse plug so close to one of the main dams is not optimal, as breaching of the fuse plug might endanger the dam. A location further away from the dams was however not practical due to high construction cost.

If under adverse circumstances the spillway does not provide enough capacity to divert the incoming water and to maintain the water level below El. 629.5 m the fuse plug will be overtopped and will rapidly erode, diverting the large discharge.
downstream. Discharged water will flow down the steep fuse plug canal to the bottom of the uninhabited Desjarárdalur valley and along this some 9 km where it will enter the Jökulsá á Dal main river course. The maximum discharge through the fuse plug is estimated to be up to 6000 m$^3$/s. The breaching and erosion of the fuse plug will lower the water level in the reservoir to about El. 618 m, causing about 370 million m$^3$ of storage to be lost from the reservoir in about 24 hours. The resulting flood will be almost six times larger than the maximum flood ever observed in the river.

**Conclusion**

The flood design for the Hálslón reservoir had to account for the special circumstances of 80% of the drainage basin being covered by the Vatnajökull glacier. Three types of potential floods were identified, a glacial melt flood due to unusual warm weather during a summer period, a PMF flood due to PMP on frozen ground and a catastrophic flood due to volcanic eruption under the glacier. The Kárahnjúkar dam spillway is designed to pass the 1000 year glacial melt flood without damage to structures but with possible erosion in the downstream canyon. The spillway is also designed to pass the PMF flood, but with limited damage to structures tolerated. A fuse plug in the Desjarárdistífla dam is designed to pass a catastrophic flood up to 6000 m$^3$/s that might result from a volcanic eruption under the glacier.

**References**


