Landsvirkjun
Góðir straumar í 40 ár

22.08.2006

Kárahnjúkar Project

Halslon reservoir impoundment

Dam site investigations, design and construction

Introduction

In view of the upcoming impoundment of the Halslon reservoir, Landsvirkjun considers it appropriate to inform the public on some technical matters in regard to the dams. In addition, a public debate has evolved in recent weeks that may not in all cases be based on actual facts due to lack of detailed information on the Karahnjukar project. With this memorandum we hope that some debated issues may be clarified.

International methodology for site investigations, design and construction.

The investigations, design and construction of the Kárahnjúkar dams have been approached in the manner of international state-of-the-art practice. Preliminary investigations are first performed before decisions are made to proceed with the project to the next level of more advanced investigations and design. At the time of final decision to proceed, investigations need to be sufficient to confirm structural safety of the site as a dam foundation and the approximate estimated investment costs.

After decision to proceed and financing of the investment, investigations continue during construction to provide data for detailed design. The drilling program and actual excavations reveal the detailed geology of foundations. Due to the size and complexity of this type of projects, all dam projects undergo changes during construction to adapt to actual conditions.

A Panel of Experts (POE), consisting of international dam experts, assisted Landsvirkjun and the designers in the original evaluation of the dam alternatives in the year 2000. The POE, has visited the project five times since construction started in

2003, to review the incoming data from investigations and oversee design adaptations to the actual conditions.

Geology and engineering up to year 2000

The first proposals of dam projects in this area date back to the sixties and the seventies. In this period overall geological mapping of the area north of the Vatnajökull glacier started, mostly in the eastern part. The western part was mapped in considerable detail in the nineties. Initial studies were made by geologists of the National Energy Authority (Orkustofnun) till 1990. Jarðtæknistofan og Jarðfræðistofan Ekra later conducted geological studies for Landsvirkjun in the years 1992 - 2005.

Dams at the general current location of the Kárahjúkar dams were part of pre-feasibility studies in 1978 related to the Austurlandsvirkjun (East Iceland Project) studying ways to harness all three glacial rivers in Eastern Iceland. A separate focus on the Kárahnjúkar Project followed and an Appraisal Report was issued by Landsvirkjun in 1992 which includes a high dam at this location.

Landsvirkjun initiated detailed geological investigations at the dam site area in 1992 and core drillings started in 1995. In the year 1996 a separate mapping and study of fissures was made mostly on the basis of careful logging of the exposed rock of the high Hafrahvammar canyon walls, the Sauðá canyon and other nearby openings.

As of 1997 the drillings and investigations were very extensive and a 50 meters long exploratory tunnel was excavated at the site of the Kárahnjúkar Dam in 2000 for further verification of the actual bedrock conditions.

The Kárahnjúkar ridge on the east side of the Hafrahvammar Canyon was created by volcanic eruption under glacier some 250 thousand years ago and thus the main formation of the ridge is the so-called móberg rock formation. The underlying bedrock is formed by solid layers of older basalt lava flows, compressed by the ice during the glacial periods. A glacial lake to elevation of 560 m a.s.l. was formed after the glacial period in the valley from Kárahnjúkar up to the glacier and the canyon was gradually formed by river erosion.

The Karahnjukar dam site is covered with a layer of glacial moraine, relatively thick on the west bank of the canyon. The rock lineaments and dikes could be traced in the open rock surfaces in the canyon, in the 50 meters long exploratory tunnel on the west bank and in some boreholes, and were later exposed on the rock surface after removal of the overburden.

The conclusion at the time on the age of faults was that the nearest active fault zone was some 12 to 15 km to the west, related to volcanic activity at Kverkfjöll, as defined by Icelandic specialists and shown on a map issued by the Icelandic Institute of Natural History (Náttúrufræðistofnun) in 1998. Icelandic earthquake maps for determination of loads on structures also defined the whole of East Iceland, including the site of the Kárahnjúkar dams, as a low seismicity region.

A Project Planning Report by VST and Palmi Associates was issued in 2000 and updated in 2001 by Karahnjukar Engineering Joint Venture. The geologists and the design engineers concluded at that stage that the investigations were sufficient to decide on the dam project. A POE with international dam experts was called in for consultation and confirmed on the basis of existing data that a high rockfill dam could be built safely at the Kárahnjúkar site.

At the same time an environmental impact assessment process was initiated for the project on the basis of the layout and design of the Project Planning Report.

The design team evaluated a solid concrete dam of the RCC type (roller compacted concrete), a rock fill dam with a central core of moraine or asphalt concrete and a rock fill dam with concrete face, CFRD. The last option was selected for the high dam across the canyon, mostly because this type with the entire body freely drained is one of most stable alternative in the event of earthquakes. This selection was confirmed by the POE taking into account also flexibility in the construction schedule and acceptable estimated investment costs. Rock fill dams with central core of moraine were selected for the saddle dams, considering safety, available fill materials and costs; the POE also confirmed this selection.

Geology and engineering in 2000 - 2003

Kárahnjúkar Engineering Joint Venture (KEJV) with VST, Almenna verkfræðistofan and Rafteikning of Iceland, the US firm Harza (now Montgomery Watson Harza) and

the Swiss firm Electrowatt (now Pöyry Energy) was selected to lead the investigations and design to the next phase, bid design and bid documents for competitive bidding. Tender design investigations were performed in 2001 and 2002 and tender documents for the Karahnjukar dam were issued in August 2002.

During the preparations of the bid documents the geological investigations continued to better define the foundation and to obtain detailed information on sources and quality of fill materials. Construction of an access tunnel in the west bank into the diversion tunnels started in November 2002 as preparatory work and the actual rock could thereby be inspected further for confirmation of the rock conditions.

In early 2002, the axis of the Kárahnjúkar dam was moved slightly to the north and turned slightly clockwise to accommodate a spillway structure at the west end of the Kárahnjúkar dam instead of the east end of the Desjarárstífla dam. This new location of the spillway was decided by the Minister for the Environment in the EIA verdict in December 2001.

Design criteria for the dams were developed in the period 2000 to 2002 by the design team. These were based partly on advice on earthquakes obtained from the Earthquake Engineering Research Center and discussions with seismic experts at the Icelandic Meteorological Office. The crustal subsidence resulting from the impounding of the reservoir was also evaluated and a settlement of the reservoir floor was estimated as up to 30 centimeters in the long term. Comments from other geologists concerned with crustal movements and fissures were reviewed and addressed.

The dams were designed to withstand strong earthquakes even though the area is outside the main active earthquake zones of Iceland. In the original conservative design criteria it was anticipated that the earthquakes could originate at known earthquake zones in Iceland, at a nearby fault or be triggered by reservoir impounding. The design criteria assumed ground accelerations that were several times more than the Icelandic standard for earthquake loads prescribes for this region. In the tender documents in August of 2002 there were specifications for special treatment of lineaments in the dam foundation.

Before final decision to proceed was made, the US engineering firm Framatome conducted an independent review of the project on behalf of Alcoa with special emphasis on the high Kárahnjúkar dam. All available geological data as well as

concern comments from geologists were reviewed. The conclusion was that the preparations for the project were thorough and in accordance with international state-of-the-art practice. The project was found to be sound.

Final decision to proceed was made in March 2003, after signing of a power sales agreement with Alcoa. Bids for the construction of the Kárahnjúkar dam had by then been received and the contract could be awarded. The lowest bidder for the construction of the Kárahnjúkar dam was the international contractor Impregilo, Italy, who has constructed many high dams in other parts of the world before and has a record of good quality work.

A group of engineering firms under the leadership of Mott MacDonald of Great Britain was retained to oversee the construction on behalf of Landsvirkjun with respect to quality of the work and control of costs and time schedule. This supervision group also includes Coyne & Bellier of France, Sweco of Sweden, Norconsult of Norway and Línuhönnun, Hnit and Fjarhitun of Iceland.

Geology and engineering during construction

Faults across the foundation of the Kárahnjúkar dam and the foundation of the Desjarár dam were seen in more detail after the overburden had been removed for foundation preparation. The action taken was to detail design the crossings of the faults at the concrete toe wall in the canyon, at the concrete footings on the west bank, and at the Desjarar dam taking into account the actual site conditions. These measures allowed for fault movements even though movements in these faults were considered to be very unlikely. Further, sealing measures for the concrete toe wall foundation and in the bedrock are made possible by grouting tunnels and galleries especially constructed under the Kárahnjúkar dam for this purpose.

Geothermal activity in the area had been part of the earlier investigations, but in July 2004 geologists from the Icelandic research institute ISOR were assigned by Landsvirkjun to investigate and map in more detail the geothermal activity in the reservoir and dam area. This investigation revealed in August 2004 that a fault at Sauðárdalur, 5 km upstream of the dam, on the west side of the reservoir at a relatively high elevation, had moved after the last glacial period. Also warm springs were found to be more widespread in the area than hitherto known, mostly controlled by

Northeast-Southwest trending fractures and faults. Warm springs and borehole temperatures showed a thermal anomaly in the area of the Kárahnjúkar Dam.

This investigation was continued in 2005 and the last movement of the Sauðárdalur fault is now believed to have been 4000 years ago. In autumn of 2005 two more faults closer to the dam were found to have moved after the glacial period. These trend towards the western and eastern ends of the Kárahnjúkar Dam.

The general conclusion is that the Kverkfjöll fault swarm extends further to the east than previously believed.

Since the discovery of crustal movement near the dams after the glacial period in 2004, the potential earthquake action from various possible sources, such as volcanic, tectonic as well as reservoir triggered ones, has been reviewed by the Icelandic seismic consultants. Due to the conservative initial design parameters, this review did not result in any changes in the design specifications. Crustal movements due to increased pressure in faults during the filling of the reservoir have also been estimated and accounted for by the design engineers.

Conclusions on crustal movement

The risk of natural crustal movements of volcanic and tectonic origin under the dam foundations and in the general Kárahnjúkar area during the lifetime of the project is considered very low. Displacements of faults due to reservoir loading are considered likely and were always expected. The magnitude of the displacements have been estimated through numerical modeling. Concrete foundations are provided with series of defense measures to control leakage.

The upstream toe of the Kárahnjúkar dam is covered with a thick layer of earth fill material as an additional automatic self-healing measure in case of crack openings. The specially installed grouting tunnels and galleries can also be used at any later time to drill and inject cement gout mixes into openings and to further seal the bedrock below the dam if necessary. It should be noted that the potential movements may cause leakage under and through the Karahnjukar dam but this does not endanger the stability of the dam.

High CFRD dams in narrow valleys

The concept of Concrete Faced Rockfill Dams (CFRD) gained popularity in the world by mid last century when heavy vibratory rollers were introduced to obtain good compaction of the rock fill. Thereby the risk of cracking of the concrete membrane due to settlement of the rock fill was dramatically reduced.

Due to its success, this type of dams has grown ever higher, and several dams in the 200 meters range have been built or are under construction around the world, among those the Kárahnjúkar dam. Some face slab cracking has recently occurred at 3 very high CFRD dams in narrow valleys. This has caused leakage, but the safety of the dams has not been questioned.

Possible face slab cracks and mitigation measures

The design team and the POE for the Kárahnjúkar dam have evaluated the recent incidents of face slab cracking due to rock fill settlement and compared with the conditions at Kárahnjúkar. The Kárahnjúkar fill is in fact very well compacted, the rock fill is of good quality and settlements have been relatively low and close to the estimates.

The general conclusion is that the probability of cracks in the Kárahnjúkar dam face slab is lower than for those dams. Defense measures have been taken to prevent cracking and minimise leakage in case of cracking. This is done by various measures at joints where concrete slabs meet, by covering the joints with special membranes and by covering the upstream face with earth fill material up to about the middle height of the dam.

Reservoir filling and monitoring

The filling of the reservoir will start in the second half of September 2006. The reservoir will be approximately half filled during autumn of 2006, stay at a stable level during the winter, allowing stabilization and close monitoring of the first stage of filling. In the summer of 2007, the reservoir will be filled at a slow rate to top level.

The behavior of structures and the reservoir area will be closely monitored and analyzed simultaneously by the respective experts in the various scientific fields.

Leakage will be monitored, as well as settlements and general movements of dam fill and concrete face slab and foundations, movements of the reservoir surroundings, groundwater pressures, concrete stresses etc.

The timing of the impounding is very important. It is technically favorable and safer to impound to a medium level, allowing the bedrock at least half a year to gradually saturate before continuation next spring. This reduces the risk of crack openings in the bedrock by differential water pressure and reservoir triggered movements. The second stage of filling during summer of 2007 is planned to proceed at a very slow and controlled rate.

Reservoir leakage

A leakage of some hundreds of l/s is anticipated through the dams and the grout curtain under the dams. The curtains are made by drilling to a depth of up to 100 m and injecting cement grout at high pressure to fill all voids in the rock. The main leakage paths however with estimated total quantities of some m^3/s are through the rock further below and through the ridges east and west of the dams in a northerly direction.

All reservoirs leak. The amount of leakage is pending on rock conditions, sealing measures, pressure and length of leakage paths. Compared with several other reservoir sites in Iceland, the Kárahnjúkar reservoir basin is not assessed to be very leaky.

The leakage in the Kárahnjúkar dam area is considerably reduced by the grout curtains and other sealing measures such as fill in the canyon upstream of the dam. The upstream cofferdam used to divert the river into the diversion tunnels is a sealing in the canyon by itself. The entire space between the cofferdam and the toe wall of the dam has also been filled with earth fill material as a sealing measure.

It has been estimated by 3D modelling that the initial leakage from the reservoir could at full lake level amount to some 5 m^3/s and gradually decrease with time by self-sealing by the river sediments, as experienced in other glacial river systems in Iceland and elsewhere. In comparison, the maximum flow through the turbines is 144 m^3/s and the average inflow into Halslon reservoir is 103 m^3/s. This order of magnitude leakage has been taken into account in the economical studies since the first planning of the project.

The model permeability accounts for fissures and cracks in the bedrock although these are not modelled separately. However, considering a specific fissure in the foundation opening of 100 mm in a critical area, e.g. underlying the Kárahnjúkar dam, the total leakage may increase initially by somewhere between 0,5 and 1 m³/s.

Review by POE

The sixth POE meeting with the designers, the site supervision, geologists and geophysicists took place this mid August 2006.

Procedures for safe closing of the diversion tunnels and the filling of the reservoir have been thoroughly discussed and mutually agreed.

Based on the conclusions of the consultants and the POE, Landsvirkjun is confident to start the filling of the Halslon reservoir next month as planned.