Challenges during the construction and completion phase of the Kárahnjúkar Project, Iceland

Abstract

The Kárahnjúkar Project in Iceland is actually the biggest European Hydrel Project under construction (2003-2009) with an installed power of 690MW. The project contains 5 dams, wherefrom the largest is a concrete-faced rock fill dam 730m long and 193m high. The total length of the tunnels involved is about 72km. Most of the headrace tunnels were drilled with 3 hard rock TBMs. Steel fibre reinforced shotcrete was applied for rock support and the inner lining, using liquid alkali free accelerators. Concrete and shotcrete was produced from 7 site batching plants.

From the external rock consolidation, the access tunnels, the headrace tunnels with or without TBM advance to the power house and the shafts, all rock support was performed with shotcrete equipment using the wet process. Dry process shotcrete was not allowed in the whole project. For the small diameter tunnels, where normally dry process is applied, an extra small wet process shotcrete rig had to be assembled. The shotcrete equipment on the 3 TBMs had to be very economical, due to the fact that the rock quality was assumed to be high strength basalt and little quantities of shotcrete were expected. The inner lining shotcrete systems for the headrace tunnel were directly assembled from the contractor, based on individual components with the aim to be able to spray and to pump concrete with the same equipment.

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Introduction

The total construction period of the 690 MW Kárahnjúkar Hydroelectric Project in the eastern part of Iceland is from 2003 until 2009.
Construction works began in spring of 2003 and all 6 generating units started to go into full service by end of October 2007.
The very tight construction schedule over a period of 4.5 years has put many constraints on the project mainly due to unforeseen geological conditions at the site.
The main features of the project are the 193 m high concrete faced rock fill dam, being the highest in Europe of such kind, and the extremely long semi horizontal headrace tunnel of 40 km length in one stretch plus access and side tunnels, another 20 km. The gross head is 600 meters and two parallel vertical steel penstocks of 450 m height, among the highest in the world, conduct the water to the 6 high head Francis turbines which are equipped with high efficiency splitter blade runners. The Power plant is primarily being constructed to supply electricity to a new Aluminium smelter being built by Alcoa of USA at a distance of approximately 50 km on the east coast. The future annual production capacity of Aluminium will be 345'000 tons. Developer and Owner of the Kárahnjúkar Power plant is Landsvirkjun, The National Power Company of Iceland.

Construction of the Karahnjukar Project

The construction work is being carried out under more than 30 main contracts by both local and International construction companies and manufacturers. Design and site supervision is performed by a number of International and Icelandic engineering organizations. Overall project management and co-ordination of works are executed by the Owner.

After diversion of the river (Jökla) in December 2003 and subsequent excavation in the river canyon it became apparent, that faults in the rock bed were crossing the dam foundation. Special measures for fault treatment had to be undertaken and the massive concrete toe wall in the canyon had to be re-located and re-designed. This delayed the dam construction by many months and concreting work on the toe wall (80.000 m3) had to be carried out throughout the winter 2004/2005 at severe winter conditions. In spite of this delay rock filling of the dam (8,5 Mio m3) and concreting of the water sealing face slab (approx. 100.000 m2), could be concluded in time to allow start of reservoir water filling according to the original schedule in September 2006. This was made possible by working through all winter 2005/2006 in harsh arctic climate on concreting of the face slab and finishing it and the dam filling up to the required minimum height of 590 m above sea level. prior to water filling. The remainder of the concrete face slab was constructed after water filling had started and was finished by end of 2006. The 7 m high concrete parapet wall on the top of the dam as well as the spillway chute were completed in summer 2007. The water level had risen already 125m by March 15th 2007 and 180m at the beginning of October 2007 and was at full level of 625 m above sea level. by mid of October 2007.
By modifying and accelerating construction procedures and sequences for the dam and related structures it was secured that the dam was completed and that the Power plant would be capable of providing full power to the important customer during coming winter 2007 and spring 2008, until the next summer flood and glacial melt will fill the completed reservoir again this summer.
Another major obstacle along the project route were difficult geological conditions in the headrace tunnel. The main part of the 40 km long headrace tunnel was excavated by 3 open hard rock tunnel boring machines (TBMs) of 7,2-7,6 m diameter. The three TBMs were purchased from the Robbins Company. All three TBMs encountered difficulties and were slowed down or held up significantly by heavy ingress of water (TBM3), fractured rock and loose in-fills (TBM2) and by soft sedimentary layers (TBM1).

Figure 1: Assembled TBM2 ready to be moved to the start for drilling

TBM3 was first stopped prematurely due to water ingress and slow pace and was turned around to drill towards TBM2 leaving the remaining tunnel section (approx. 1 km) to be drilled and blasted the conventional way. This change of construction method saved 3-4 months in construction time for the respective section.
TBM2 got stuck twice in loose rock and fault zones with gravel infill and water ingress and was practically held up for 6-7 months, progressing only some 70 m during remedial and support works in the tunnel.

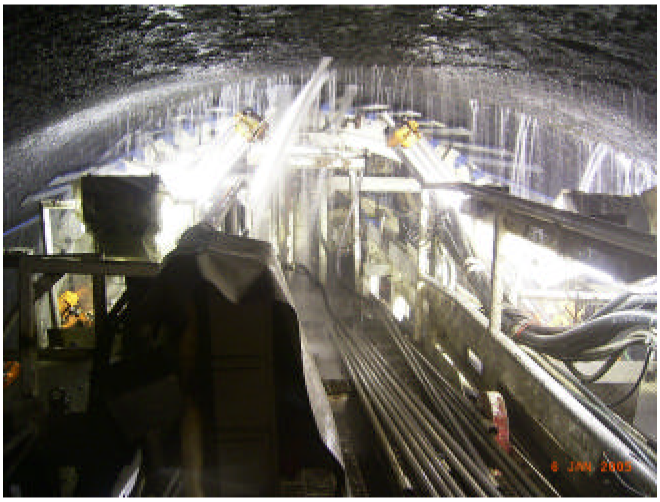

Figure 2: Heavy water ingress at TBM3

TBM1 was slowed down due to soft layers of sedimentary material in the initial phase but broke through first of the three after some 15 km of drilling on 9 September 2006. The breakthrough of TBM3 was on 5 December 2006. TBM2 was used to bore another 8.5km of an additional 13km headrace tunnel with the last breakthrough of the project on 11 April 2008.
Despite all the difficulties during the mechanised excavation of the headrace tunnel three world records could be achieved:

- 23 June 2007: World record for TBM excavation (7-8m) of 106.12m in 24 hours
- 23 August 2007: World record for TBM excavation (7-8m) of 428.8m for one week
- 25 August 2007: World record for TBM excavation (7-8m) of 115.7m in 24 hours

Because of these delays in tunnel excavation the finishing works inside the tunnel, i.e. rock support, surface treatment, concrete structures, cleaning out, etc. became most critical for the project completion and great efforts had to be made in order to speed up those works.
Apart from increasing the workforce up to above 700 men working inside the tunnels additional equipment was brought in: Shotcrete equipment and concrete handling equipment, additional trains, etc. Transport logistics and material handling gained crucial importance. Modified designs, to allow better constructability and acceleration of the works were introduced among other things, such as incentive payments and increased working time. Drop shafts were drilled from the surface (180-200 m above tunnel) to allow more efficient transport of concrete to the tunnel. Additional access to the tunnels was also provided for, a fourth adit, and by using the surge tunnel and the surge shaft for transportation of equipment and personnel to the work fronts.
By doing all of this by joint effort of Contractors, the Engineer and the Owner the delays in tunnel excavation could be mitigated considerably.
In addition to the above described also other works have had to be adjusted to the actual situation and circumstances.

The underground powerhouse construction as well as manufacturing and installation of electro-mechanical equipment have been constructed basically according to the original schedule. Some minor delays have occurred in equipment manufacturing and in installation of the pressure shaft steel linings and hydro mechanical gate equipment which, however, did not affect the start up date.
In order to make initial power available on time to the aluminium smelter it was decided to operate the first generating unit of the power station as synchronic condenser. This was made possible by installing appropriate additional electronic converter equipment for start up of unit no. 1 from the grid. The generator was de-coupled from the turbine shaft,
which was lowered slightly, and a protective cover installed on top of the draft tube in place of the draft tube cone. With these arrangements for unit no. 1 the weak electrical network on the east coast was supported substantially, transmission capacity increased and voltage regulation with the generator provided for. Thus this allowed start-up of the aluminium smelter on time in April 2007 from the national grid with an initial supply of up to 100 MW. The two 220 kV transmission lines between power plant and smelter with a link to the existing national grid were commissioned in January/February 2007. The testing and commissioning period for the remaining generating units were then to be shortened and accelerated considerably in order to compensate for the delay in tunnel works and water availability. Two and two generating units were commissioned simultaneously on separate pressure shaft penstocks. This of course called for precise planning and additional commissioning resources. Due to further difficulties and delays in completing the headrace tunnel, however, the generating units no. 2-6 have been operationally tested with water and commissioned up to synchronization and part load operation at much reduced head water pressure flow (450 m instead of 600 m water column). The reason for this being, that it was possible to complete the lowest third (15km) of semi-horizontal headrace tunnel earlier (end of July 2007) and so enabled water filling of that section considerably ahead of the remaining tunnel sections, which were only being filled by mid of October 2007. Together with an accelerated and simultaneous start-up of the aluminium smelter this enabled both partners to be up to full production in time according to the original schedule.
This has saved 2-3 weeks of testing time for each of the generating units which could then be brought on line and operated at full power within one week each after availability of full head flow. The methodology has brought about a substantial advancement of full power production from the Kárahnjúkar plant.
The filling of the lowest third of the headrace tunnel was done by inflow of leakage water into the tunnel

and pumping, to fill that tunnel section as well as both vertical pressure shaft penstocks.
In spite of severe delays in tunnel completion the project was in full power operation by end of 2007, close to the original plans scheduled for October 2007, and all work shall be completed by end of 2008.
The main bulk of work left for this year is a second catchment and diversion area (Jökulsárveita/Hraunaveita), connected to the main headrace tunnel through a 13 km long and 7.2 m wide side tunnel that was mostly drilled by a TBM. Further tunnels and two smaller earth fill dams are also being constructed in that area.
An additional contract was signed to build a smaller dam (4'000m^3 concrete) in front the main dam to avoid erosion of the canyon due to the water fall from the spillway. This dam will be constructed in 2009.
The Project has been faced with considerable resistance and criticism by diverse opponents and environmentalists, both local and international, and has had to fight against this throughout the project period. Several protest actions have been arranged on site and elsewhere during the construction phase, but this has now calmed down.
The construction workers and the project personnel have performed outstandingly under toughest environmental conditions at the site, rough weathers, dangerous working areas and remote location away from the families and deserve recognition for their great efforts.

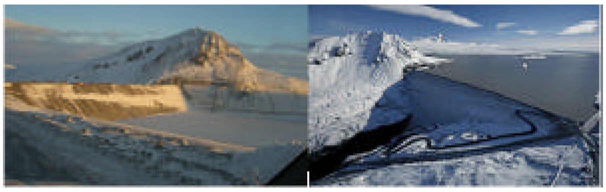

Figure 3: January 2007 and January 2008 Concrete faced rock filling dam after start of filling with water and at full water level

Concrete works

The most important concrete works were
- toe wall (80'000m^3)
- dam plinth
- concrete face slab (92'000m^3)
- spillway

To successfully follow the time schedule the arctic conditions had to be taken into account from the beginning, like
- heavy snow falls during the winter
- wind, storms with speeds up to 162km/h
- temperature falls up to -35^{o}C
- very poor visibility during winter
- unexpected weather changes through-out the whole year
- only 4 months without snow
- difficult, dangerous working conditions

For the total project 7 on site concrete batching plants were erected, which had to supply constant concrete quality with constant temperature during all the year.

Figure 4: Access to one of the headrace tunnels during the winter season

In Iceland there are no AAR resistant aggregates available. Therefore the locally produced Icelandic Portland cement (CEM II/A-M 42.5R) contains 6% condensed silica fume. This cement was used for the shotcrete mixes. For all normal concrete works a Norwegian cement Norcem CEM II/A-V 42.5R with 20% of Fly Ash was used.
Taking into account the end use of the particular concrete type, due attention had to be paid to the alkali reactivity of locally sourced aggregates in combination of the cement and to its heat generation during the hardening process.
Especially for the concrete face slab additional requirements regarding frost resistance were specified:
- water/cement ratio <0.45
- air content of fresh concrete at placement 5-7%
- Spacing factor (ASTM C457) of entrained air void system <0.20mm
- Frost resitance (ASTM C666), procedure A: durability factor >80
- Water penetration (ISO 7031) <50mm with estimated average depth of <20mm

Curing and protection in cold weather: The surface temperature of concrete had to be kept above 3^{o}C until the concrete was frost-resistant (f_c >10MPa). Additionally a curing compound had to be applied.

Figure 5: Concrete face slab: concreting under extreme winter conditions

Shotcrete systems

The following sprayed concrete types were specified:

- For underground works: shotcrete type C24/30:XC2 with compressive strength class C24/32, designed for surfaces subject to long term water contact.
- For surface works: shotcrete type C32/40:XF3 with compressive strength class C32/40, designed for surfaces subject to high water saturation and freezing.
- Accelerated sprayed mortar: as initial layer where water ingress is encountered.
- Steel fibre test according to EFNARC: plate test with >700 Joules

The project started with the pre-qualification of all specified concrete classes, followed by a regular quality control management from the contractor which had to be approved by the supervisor. In conclusion quality control always showed much better results than specified.

All the equipment for shotcrete, including the spraying devices on the three Robbins hard rock TBMs as well as the concrete pumps to all contracts of the whole project were supplied by Putzmeister and Sika within their alliance. The total amount of shotcrete applied for the project was approximately 200'000m3.

Shotcrete equipment: The whole project was using wet process shotcrete, mostly using the dense stream method, due to the fact that in Iceland dry process was not permitted. Therefore a special small wet process equipment had to be assembled for the small connection tunnels in the powerhouse. For all the access tunnels or smaller tunnels standard wet process spraying rigs were used.

Workability of the base mixes to guarantee a 6 hours workability was a big issue with the local aggregates. Therefore a specially adapted superplasticiser had to be developed.

Figure 4: Conventional shotcrete rig for rock consolidation and tunnelling support

On the three hard rock Robbins TBMs the original design was to use the wet process thin stream method with a circular installed manipulator. Before starting the drilling it was possible to convince the contractor to change from thin stream to dense stream. With the help of simulation tests outside the tunnel it could be shown, that the planned 56m of thin stream conveyance from the machine to the nozzle were not realistic. Additionally the installed circular manipulators did not work properly, so that they were replaced by small Aliva robots. This was not ideal, but the best of the possible solutions without loosing time.

Figure 5: Shotcrete manipulator on the back up of the TBM

All shotcrete was steel fibre reinforced shotcrete. A minimum stock of admixtures and steel fibres had to be guaranteed. This was not always easy due to difficult logistics to Iceland, including the stock conditions on such a remote site. In case of shortages the products had to be transported by air freight. The most important product was the liquid alkali-free accelerator, because in general those products have only a limited shelf life and show a tendency of precipitation of solid crystalline material. The only way to guarantee the required stock without having problems of shelf life was the following: The liquid alkali free accelerator was spray dried after production and transported in big bags to Iceland. There are no limits of shelf life of the spray dried powder. The idea is not new and successfully applied in milk industry. Two mixers to dissolve the spray dried accelerator powder were installed, one in a ready-mix-concrete plant at the closest place from the main camp (approximately 80km) and one directly on site.

Figure 6: Mixer for the site production of the liquid alkali-free accelerator

Figure 7: Storage of big bags of spray dried alkali-free acceleratror.

Summary

The 690MW Karahnjukar hydro power project has been one of the most challenging European projects under construction and is coming to a successful end.

Additional information can be obtained from www.karahnjukar.is

The key figures can be seen from the following table:

Installed capacity	690 MW
Generating capacity	Approx. 4,600 GWh/year
Turbines	Francis, vertical axis
Number	6
Rated discharge per unit	24 m^3/s
Rated output per unit	115 MW
Hálslón reservoir	
Area of full reservoir	57 km^2
Lenght of reservoir	25 km
Live storage	2,100 million m^3
Reservoir full supply level (FSL)	625 m a.s.l.
Reservoir minimum operating level (MOL)	575 m a.s.l.
Hálslón servoir catchment area	1,806 km^2
Average inflow to Hálslón reservoir	107 m^3/s
Kárahnjúkastífla dam	
Maximum dam height	193 m
Dam length	730 m
Fill materials	8.5 million m^3
Desjarárstífla dam	
Maximum dam height	60 m
Dam length	1,100 m
Fill materials	2.8 million m^3
Sauðárdalsstífla dam	
Maximum dam height	25 m
Dam length	1.100 m
Fill materials	1.5 million m^3
Ufsarlón pond	
Area of full reservoir	1 km^2
Maximum water level	625 m a.s.l.
Ufsarlón pond catchment area	430 km^2
Average inflow to Ufsarlón pond	31 m^3/s
Ufsarstífla dam	
Maximum dam heigth	37 m
Dam length	620 m
Fill materials	0.6 million m^3
Kelduárlón reservoir	
Area of full reservoir	7.5 km^2
Reservoir full supply level (FSL)	669 m a.s.l.
Live storage	60 million m^3
Kelduárstífla dam	
Maximum dam heigth	26 m
Dam length	1,650 m
Fill materials	0.8 million m^3
Tunnels	**Approx. 72 km**
Headrace from Hálslón (dia: 7.2-7.6 m)	39.7 km
Headrace from Ufsarlón (dia: 6.5 m)	13.3 km
3 adits to headrace (dia: 7.2-7.6 m)	6.9 km
2 diversion tunnels and adit at dam	2,4 km
Grouting galleries at dam	0.5 km
Surge tunnel (dia: 4.5 m)	1.7 km
2 diversion tunnels Hraunaveita (dia: 4.5 m)	3.7 km
2 vertical pressure tunnels (dia: 4.0 m)	0.8 km
Access tunnel to power station (dia: 7.5 m)	1.0 km
Tailrace tunnel (dia: 9.0 m)	1.3 km
Cable tunnel (dia: 4.0 m)	1.0 km
Total head	599 m
Rated discharge (maximum discharge)	144 m^3/s
Average discharge	110 m^3/s

Sika was chosen to be the supplier of all equipment for shotcrete and pumping concrete within their alliance with Putzmeister to all main contracts. Additionally Sika supplied all admixtures, membranes and steel fibres to the project for the tunnel support, tunnel linings, the toe wall, the dam plinth, the face of rock fill dam, the spillway and the power house. The concrete of the foundations for the High Voltage transmission line was produced with Sika admixtures as well.

Additionally also the admixtures, grouts and sealants for the construction of the new Aluminium smelter were supplied by Sika.

The Authors

Gudmundur Petursson graduated with M.Sc. Dipl.Ing. degree in electrical engineering from the Technical University of Darmstadt, Germany. He has over 33 years of experience in the hydropower industry, working for ABB (Brown Boveri & Cie Mannheim, Germany), MWH (Harza Engineering Company, Chicago) and Landsvirkjun, the National Power Company of Iceland. Over the years he has worked on project administration and as a resident engineer for hydropower projects in Germany, Iran, Venezuela and Iceland. He is currently the Head of the Project Management for the $1.5-billion 690 MW Karahnjukar hydroelectric project in eastern Iceland. Mr. Petursson's areas of expertise include project management, design, tender specifications, contracting, and supervision of design, manufacturing, erection and testing of electro-mechanical equipment for power generation projects. He is an active member of the Icelandic Association of Chartered Engineers and an honorary member of the Project Management Association of Iceland where he has been responsible for certification of Icelandic project managers for the International Project Management Association.

Gustav Bracher, born in 1949,
received his Ph.D. degree in Chemistry from the Federal Institute of Technology, Zürich (ETH-Z). After his studies and working as a research assistant he joined the Sika group in September 1979:

- CR&D for fundamental research in cement: Magnetic resonance study to investigate hydration and reactivity of cements, investigation of the influence of different types of admixtures, correlation between NMR relaxation measurements and compressive strength.
Measuring technology of corrosion measurements of reinforced concrete structures, including modelling of corrosion measurements of reinforced concrete lab samples.
CR&D product development in the field of repair mortars and tunnelling products like aluminate based accelerators, corrosion protection mortars, first Epocem products (combination of Epoxy modified cementitious mortars), ready-for-use repair mortars for dry and wet process.
- Technical Manager of the Tunnelling Division of Sika Switzerland. Member of the Technical Committee to set up the specifications for the pre-qualification of the concrete design for the Gotthard Base tunnel, the longest tunnel in the world.
- Corporate Marketing Field Manager Tunnelling for the Sika group: Responsible for the change of world-wide active Sika group with local Sika companies into a global organisation of the tunnelling business. Special emphasis of durability design in shotcrete technology and the production of pre-cast concrete tunnel lining segments to produce concrete without any micro-cracking.
- Corporate Key Project Manager for the Sika Group within the Business Unit Concrete
Project Manager for the Karahnjukar Hydro Power Project in Iceland.