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The Kárahnjúkar hydroelectric project: transient analysis of the waterways system

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Abstract

Landsvirkjun, the National Power Company of Iceland, intends to initiate in 2003 the construction of the Kárahnjúkar 690 MW hydropower plant. The project comprises the 190 m high Kárahnjúkar concrete-faced rockfill-dam that creates the Hálslón reservoir, two saddle dams, a 40 km long main headrace tunnel, the 14 km long Jökulsá diversion tunnel, two 400 m high-pressure shafts and an underground power station. As a function of the water level in Hálslón reservoir, the Jökulsá diversion tunnel generates free flow conditions in its upper part, and pressurized flow conditions downstream. A hydraulic jump thus appears in the Jökulsá diversion tunnel, which cannot be modeled as a simple conduit. A certain volume of the diversion will be functioning as surge tunnel during transients. The tunnel has been modeled as a conduit with a variable length, followed by a surge tunnel with an initial water level corresponding to the level of the hydraulic jump. The results revealed that the additional volume of the free-flow part significantly decreased the extreme transient pressure loadings.

Nomenclature

Term	Symbol	Definition
Pressure head	H	m a.s.l.
Flow Rate	Q	m^3/s
Tunnel diameter	D	m
Tunnel roughness (equivalent sand roughness)	k_s	mm
Tunnel roughness (Manning-Strickler)	K	$m^{1/3}s^{-1}$

Project

Landsvirkjun, the National Power Company of Iceland, intends to construct the 690 MW Kárahnjúkar hydropower plant to supply a new aluminium smelter. The plant will harness the potential of the rivers Jökulsá á Brú and Jökulsá í Fljótsdal in eastern Iceland. The first stage of the project comprises the 190 m high Kárahnjúkar concrete-face rockfill dam, on the Jökulsá á Brú, to impound Hálslón reservoir, two saddle dams, a 40 km long headrace tunnel, two vertical pressure shafts, each 400 m deep, and the underground power station. For environmental and topographic reasons the surge tank will be 1.4 km long inclined tunnel. In the second stage, water from the Jökulsá í Fljótsdal will be diverted at Ufsarlon into a 14 km long tunnel connected directly with the headrace tunnel. Jökulsá tunnel will act as a second surge tank for the combined Kárahnjúkar/Jökulsa pressure tunnel system, but the transition from free-surface to pressure flow conditions in this tunnel, which will take place at a location that will vary with the level of Hálslón reservoir, is the principal hydraulic problem needing to be analyzed during project design.

The layout of the waterways was optimized for staged construction of the power plant and to allow later construction of the Jökulsá intake and tunnel, whilst the headrace tunnel is in operation. The route of the headrace tunnel depends principally on possible locations for construction adit; its vertical alignment is determined by the need for ascending drives, to allow free drainage during construction, which also requires that the adits be sited at appropriate elevation. Maximum and minimum elevations along the headrace tunnel are governed by the minimum level of Hálslón reservoir and allowance for design surge conditions, but the maximum elevation is also limited by the need to ensure sufficient rock cover.

The headrace tunnel will cross a slightly dipping, 1500 m thick lava pile. Individual lava flows, mainly of olivine, tholeiite and porphyritic basalts, display typical zoning, with a dense central part between porous basalt and scoria layers. Individual flows are often covered by consolidated, fluvio-glacial sediments (sandstone, siltstone and conglomerates), typically 1–5 m thick. The headrace tunnel will cross several paleo-valleys filled with thick sediment deposits, mainly conglomerates and sandstone. Over the first 10 km of this tunnel, hyaloclastites (known in Iceland as móberg), which result from volcanic eruptions under an ice-cover, will be encountered; these very heterogeneous formations consist of pillow lava, cube-jointed basalts, tuffs and agglomerates.

Thanks to the generally favorable rock conditions, with respect to support and permeability, the headrace tunnel will remain largely unlined, except over the first kilometer from the Kárahnjúkar intake and two short sections with insufficient rock cover. The tunnel will mostly be excavated by TBM (in two drives), but counter drives by drill and blast are also required by the tight construction schedule.

Transient waterways system

A hydraulic transient analysis of the waterways system of the Kárahnjúkar Hydroelectric Project has been performed. This transient analysis has firstly been done for construction stage 1, consisting of the headrace tunnel (Hálslón reservoir) combined with the surge tunnel and the Bessa diversion tunnel, and secondly for construction stage 2, with the addition of the Jökulsá diversion and the Ufsarlón Pond (see Figure 1). The tested load cases correspond to opening, closing and combined opening-closing or closing-opening scenarios. The surge and water hammer calculations have been made separately. The roughness of the tunnel linings has been varied as a function of the tested load cases. The basic parameters of the different elements of the waterways system are presented in Figure 1. The frictional head losses are based on the roughness values, i.e. an average Manning-Strickler value of $K = 55\ m^{1/3}s^{-1}$ ($k_s = 10$ mm) for both TBM and D&B tunnels and a value of $K = 95\ m^{1/3}s^{-1}$ ($k_s = 0.05$ mm) for steel linings. However, for each case investigated in the transient analysis the most unfavorable head loss parameter combination has also been applied.

The pressure tunnels are excavated by TBM or Drill & Blast (D&B) and, except of some short stretches, unlined. For both construction methods the same roughness was used, because the D&B cross section has been increased in order to obtain the same head loss. For the steel lining, the Manning-Strickler value has been converted from the relative roughness coefficient following the Prandtl-Colebrook formula, and at the design discharge (48 m^3/s for stage 1 and 72 m^3/s for stage 2, for each pressure shaft). For the calculations the relative roughness coefficient k_s will be used, since for large diameter tunnels the assumption of a tunnel situated in the rough domain, according to Moody-Stanton diagram, is questionable. For the above given range of head loss coefficients, the extreme values due to water hammer are normally only very little influenced by the head losses. However, the maximum upsurge and downsurge in the surge tunnel are mainly influenced by the head losses in the headrace tunnel upstream. Local head losses have been introduced in the model at the 90° bend at entrance of surge tunnel and at the rectangular orifice at entrance of Bessa diversion tunnel.

The water hammer and surge calculations were carried out by use of the powerful and user-friendly computer program Hydraulic System, which was developed at the Laboratory of Hydraulic Constructions (LCH) of the Swiss Federal Institute of Technology in Lausanne, Switzerland. The program uses the method of characteristics to solve the one-dimensional transient flow equations. The waterways system can be subdivided into a series of elements that are available in a library (pipes, tunnels, surge chambers, tanks, reservoirs, valves, turbines, junctions, pumps, throttles, orifices, crest overflow etc.) on a graphical window. At every node of the system and for every time step Δt, the calculated results can be visualized and transferred into any spreadsheet environment. Hydraulic System uses the Microsoft Windows environment and is characterized by a visually based, user-friendly approach.

The turbines are modeled as a discharge element. A time-discharge law simulates the powerhouse operating conditions. The Bessa and surge tunnel storage reservoirs are fictitious reservoirs and only serve to compute the total spilled volume. The second stage of the project involves the construction of the Jökulsá tunnel, relating the Headrace tunnel at Adit 2 with the Ufsarlón pond. For most operating conditions, the Jökulsá tunnel generates free flow conditions in its upstream part, and pressurized flow conditions downstream. A hydraulic jump thus appears inside the tunnel, and its exact location changes with the discharge in the tunnel and the water level in Hálslón reservoir. Therefore, this tunnel cannot be simply modified as a pressure conduit. Depending on the location of the hydraulic jump, a certain volume of the

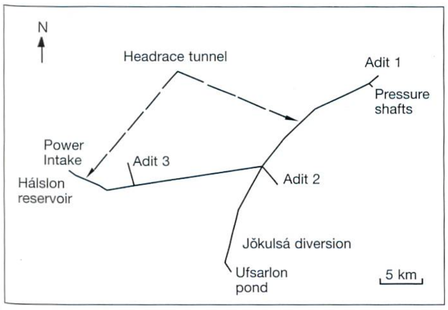

Fig. 1. Schematization of the transient waterways system.

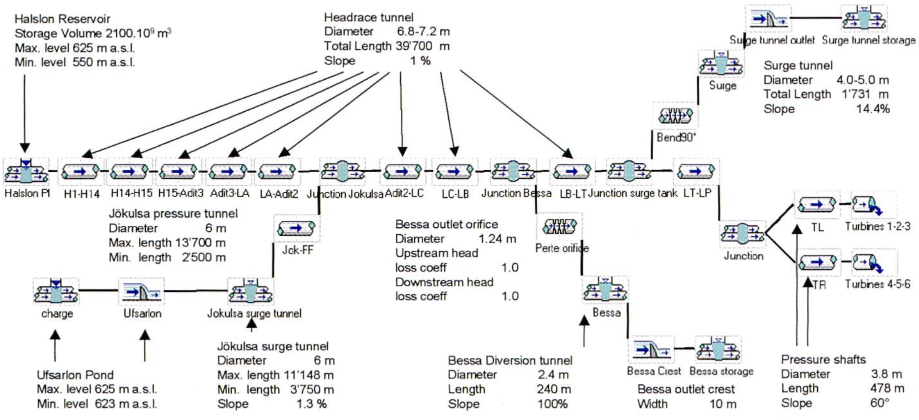

Fig. 2. Numerical scheme of the transient waterways system in stage 2 of the project.

tunnel is functioning as surge tunnel during pressure transients. The tunnel has been modeled as a pressurized conduit with a variable length, followed by a surge tunnel with an initial water level corresponding to the level of the hydraulic jump. The water level – volume relationship of this surge tunnel is dictated by the geometry of the Jökulsá tunnel. In this way, during the transient calculations, a correct simulation of the water mass volume in the tunnel and of the total possible friction losses has been accounted for. The total hydraulic system is presented in Figure 2.

The investigated load cases covered both of the construction stages. Several combined opening-closing and closing-opening scenarios have been calculated, as well as a closing case with the two reservoirs at 625 m a.s.l. at 144 m^3/s of total discharge. The opening procedure generates 10% of the maximum discharge within 120 s, followed by an increase up to 100% in 30 s. The closing scenario lowers the maximum discharge down to 10% of its value within 7 s and down to 0% within 17 s (emergency shutdown). It is considered that these opening and closing scenarios correspond to critical loading conditions of the network. The re-opening or re-closing were performed at the most critical moment, i.e. when the water is flowing with the highest velocity downstream respectively upstream the pressure tunnels. For each of the loading cases, a water hammer calculation and a surge oscillation calculation have been performed separately. This is necessary because of the different time steps they use: for water hammer, time steps of 0.05–0.20 s were typical, whereas for surge oscillation calculations, time steps of 5–20 s have been used.

Results of the calculations

Some surge and water hammer results of the load cases (shown in Table 1) are compared in Figure 3.

It can be seen in Figure 3a that the closing procedure for stage 2, with a total discharge at the turbines of 144 m^3/s, generates maximum pressures throughout the transient system that are very comparable to the ones for stage 1 with only 96 m^3/s of total discharge. This is due to the favorable effect of the upstream free flow part of the Jökulsá diversion, which acts as an additional surge tunnel during severe transients.

Figure 3b shows that the water hammer pressures are slightly higher during stage 2, however, the surge oscillations are very similar. As outlined before, the maximum pressures at the turbines are obtained by a superposition of water hammer and surge oscillations. Obviously, the initial water hammer pressures at the turbines travel through the 40 km long headrace tunnel at a wave speed of about 1300 m/s, i.e. in a time period of about 60–65 seconds they are reflected upstream and arrive at the turbines downstream.

Furthermore, Figure 3c presents the surge tunnel oscillations during stage 1 and stage 2 for a tunnel diameter D = 4.5 m and a tunnel roughness k_s = 3.8 mm. It can be seen that the maximum and minimum levels of oscillation in the surge tunnel are very comparable in both cases. The calculated difference of only a few meters of pressure head is insignificant regarding the precision of the calculations and the total pressure head in the transient system.

Finally, Figure 3d shows the surge tunnel oscillations for the opening-closing procedure during stage 2, for different tunnel diameters and a roughness of k_s = 10 mm. While the maximum surge pressures are similar to the closing procedures as presented in Figure 3c, the minimum surge pressures are very low but still higher than the entrance of the surge tunnel.

Conclusions

The calculations of the stage 1 and stage 2 transient pressures in the waterways system have been performed for different closing, opening and combined opening and closing emergency load cases. Furthermore, different surge tunnel diameters and roughnesses

Construction stage	Loading	Hálslón tunnel		Jökulsá tunnel	
		Discharge	Level	Discharge	Level
1	closing	96 m^3/s	625 m a.s.l.	–	–
2	closing	74 m^3/s	625 m a.s.l.	70 m^3/s	625 m a.s.l
2	opening-reclosing	74 m^3/s	625 m a.s.l.	70 m^3/s	625 m a.s.l

Table 1. Load cases.

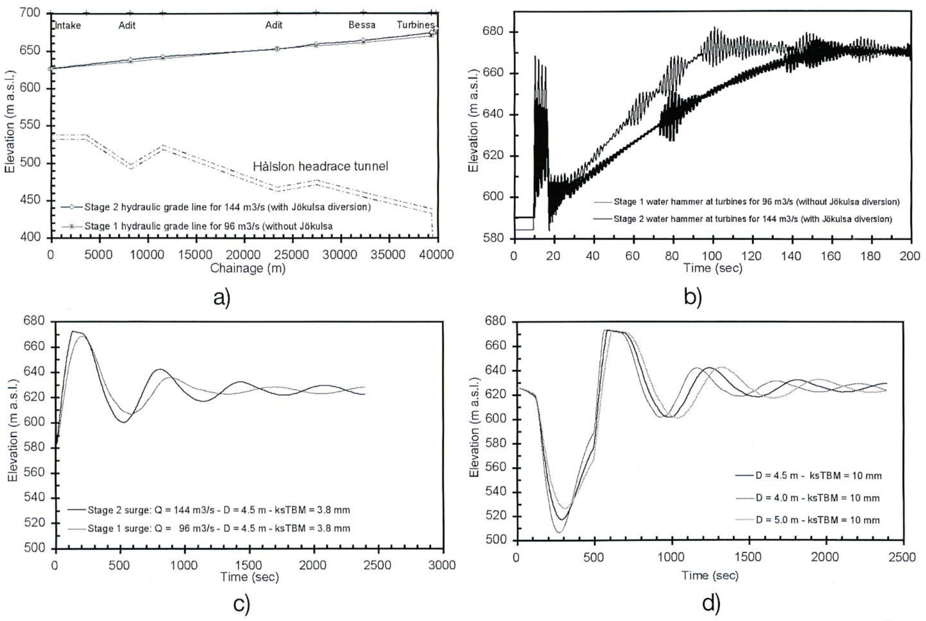

Fig. 3. Results of the transient calculations: a) Hydraulic grade lines for stage 1 (96 m^3/s) and stage 2 (144 m^3/s) closing procedures; b) Corresponding water hammer at turbines; c) Surge tunnel oscillations for stage 1 and stage 2 closing procedures and a tunnel diameter of D = 4.5 m; d) Surge tunnel oscillations for stage 2 opening-closing procedure and different surge tunnel diameters.

have been tested. The resulting maximum pressures throughout the system, as well as the corresponding surge tunnel oscillations, indicate that the construction stage 2 load cases, with a total discharge of 144 m^3/s, results in maximum water pressures that are very comparable to the ones for construction stage 1, with only 96 m^3/s of total discharge. This phenomenon is due to the fact that the upstream part of the Jökulsá diversion tunnel in construction stage 2 is characterized by free-flow conditions and thus acts as an additional surge tunnel volume during transients.

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