The model tests of the bottom outlet of the Kárahnjúkar hydro-electric project

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ABSTRACT

This paper deals with the hydraulic model tests performed at Hermann Grengg Laboratory of the Graz University of Technology for the bottom outlet of the Kárahnjúkar dam in Iceland. The scale 1:15 hydraulic model of the bottom outlet reproduced the gate chamber, the free-flow tunnel down to the flip bucket at the tunnel end, the flip bucket itself and part of the canyon (jet impingement area). This enabled the study of the performance of the bottom outlet – a structure remarkable for its extraordinary dimensions with high velocities and flow rates – and provided the basis for proposing the required optimisations. The studies are now complete and will be discussed in this publication.

Introduction

The Kárahnjúkar hydropower project currently under construction by the Icelandic national power company Landsvirkjun is planned to provide the power needed for running an aluminium smelter in the East of Iceland. The contract for constructing the Kárahnjúkar hydraulic model came from Landsvirkjun, which will then also operate the power scheme. The design of the project was in the hands of Karahnjukar Engineering Joint Venture, with Montgomery Watson Harza (MWH) responsible for design of the bottom outlet. Palmi Johannesson of Palmi Associates acted as subcontractor to MWH. The hydro-electric development is due to begin operation in 2007 and will be completed late 2008.

The power station, equipped with 6 Francis turbines, will have a capacity of 690MW and generate an annual 4600GWh.

The water driving the Kárahnjúkar power station will be supplied from the rivers Jökulsá á Dal and Jökulsá í Fljótsdal feeding several reservoirs. The rivers rise in the Vatnajökull glacier in eastern Iceland. The Kárahnjúkar dam impounds the Jökulsá á Dal to create the Hálslón reservoir. The water from the Hálslón reservoir, together with the flows from the Ufsarlón reservoir, will be conveyed in a headrace tunnel to the power station at the Teigsbjarg escarpment to the north-east. Figure 1 below is a location map showing the planned scheme.

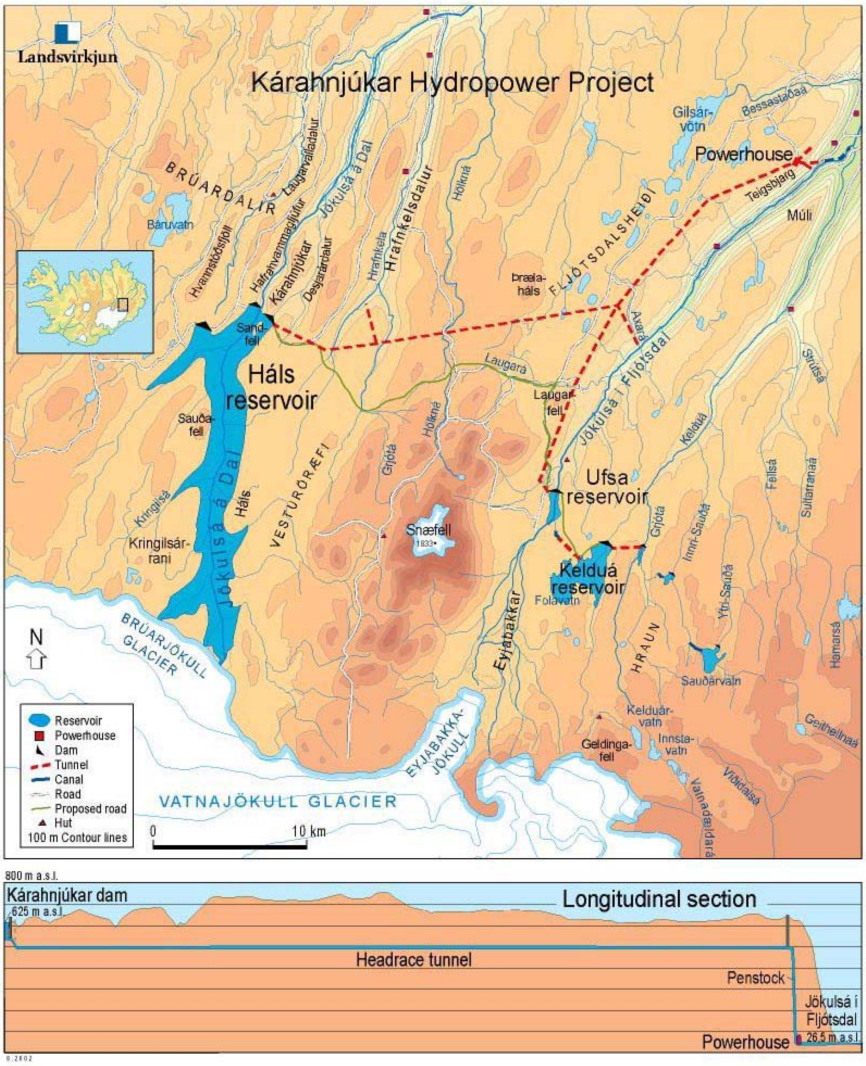


Figure 1. Location map of the Kárahnjúkar project

The Kárahnjúkar dam, 696m long and 198m high, is a concrete-faced rockfill (CFR) structure with a fill volume of 8.5 million m³. This CFR dam will be among the largest of its kind worldwide and the highest in Europe. The flows of the river are diverted during construction in two diversion tunnels to the west of the reservoir, the inner one being converted into a bottom outlet from the reservoir. Flood discharge will be through a spillway arranged in the slope to the west of the dam, followed by a chute. The Hálslón reservoir to be created by the Kárahnjúkar and two further small dams will have a volume of 2.1 billion m³ and rely on a mean inflow of 107m³/s. Top water level will be 625m and the lowest operating level 550m above datum.

The bottom outlet will be capable of a discharge of about 350m³/s for maximum gate opening and with a full reservoir, which will place it among the largest facilities of this type worldwide.

The hydraulic model test

The Kárahnjúkar hydro power project is an extraordinary big project, mainly concerning the dimensions of the construction and the machinery. High expected flow velocities and discharges in the prototype ask for additional tests of the spillway and the bottom outlet besides numerical calculations. Therefore the optimisation studies needed to ensure the good functioning of the bottom outlet at the Kárahnjúkar dam were conducted on a hydraulic scale model at the Hermann Grengg Hydraulic Laboratory of the Graz University of Technology. The Laboratory boasts many years' experience in conducting scale model studies for bottom outlets (INSTITUTE FOR HYDRAULIC ENGINEERING, 1983, 1991, 1997, 2003). The model built for the study at scale 1:15 reproduced the bottom outlet from the gate chamber down to a flip bucket at the end of the outlet plus a canyon length of 150m as the jet impingement area. The scale model tests served to study and optimise the following parameters:

- Performance test for all bottom-outlet components
- Determination of bottom-outlet discharge capacity
- Pressure-head distributions in high-pressure and free-flow sections
- Bottom-outlet aeration and flow velocities
- Flow pattern in the free-flow tunnel
- Flip bucket geometry
- Erosion in the jet impingement area

Model set-up

As mentioned before, the hydraulic model of the Kárahnjúkar bottom outlet was built at a scale of 1:15 at the Hermann Grengg Laboratory of the Graz University of Technology. The large scale was selected mainly in order to obtain realistic air-entrainment results that lent themselves to transfer to prototype conditions. The model was run on the basis of Froude similitude. Figure 2 below shows two photos of the model constructed at the laboratory. Practically the whole model was built in plexiglass. The only exceptions were baffles and modifications introduced for studying variants (Trovidur and steel plate). The wall bordering the canyon was built in traditional brick, and the canyon bottom was levelled with coarse gravel, which was also used for building the slopes.

Figure 2. Photos showing overall model and gate area

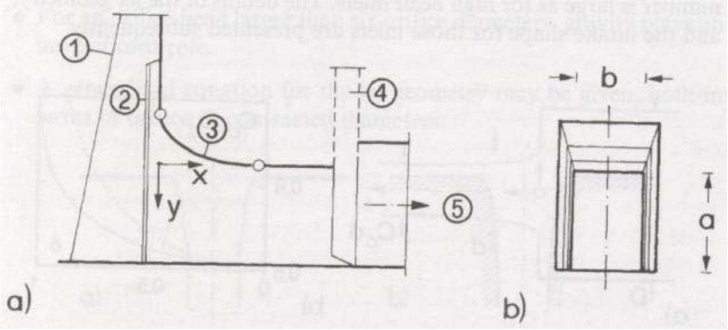
The transition from the substantially larger horseshoe section of the upstream pressure tunnel to the smaller rectangular shape of the gate chamber is formed by an inlet trumpet rounded to an elliptical cross section. The elliptical geometry (Figure 3) can be expressed as follows (see also VISCHER & HAGER, 1998).

$$(X-1)^2+(Y/0.32+1)^2=1$$

where $0 < X < 1/3$
and $X = x/a$ or $X = x/b$ and $Y = y/a$ or $Y = y/b$.
a, b are the height and width of the small cross section.

$$(X-1.2)^2+(Y/0.16+1)^2=1$$

where $1/3 \leq X \leq 1$.



Intake geometry of high-head intake (a) longitudinal section, (b) cross section with ① upstream pier face, ② trashrack, ③ transition curve, ④ gate with gate slot, ⑤ penstock

Figure 3. Inlet geometry (VISCHER & HAGER, 1998)

Downstream from the elliptical transition, the roof, side walls and invert run parallel, except for a short section in the gate slot area. Three metres below the service gate the side walls distinctly recede both vertically and horizontally directly at the first aerator (see also Figure 2, right). The horseshoe-shaped tunnel chute is horizontal over a first 60m section and then slopes at 5%.

Instrumentation

Hydrostatic pressure head was measured at more than 250 locations distributed over the whole length of the model, using single-point measurements. In addition to dynamic pressure head measurements, which will not be discussed here, air flow was measured by use of a TSI VelociCalc® hot-wire air velocity meter. Water velocity was measured by use of a high-speed camera (which will also not be dealt with in greater detail here). Air flow was measured at the inlet to the aeration gallery upstream of the rectangular cross section.

The results

The following paragraphs will briefly discuss the results of the model studies for the Kárahnjúkar bottom outlet.

Bottom outlet discharge capacity

Bottom-outlet discharge capacity was determined for different service gate openings and reservoir levels. The maximum discharge capacity of the bottom outlet was measured to be 341m³/s with a full reservoir. Figure 4 below shows the measured flows plotted against reservoir level for different gate openings.

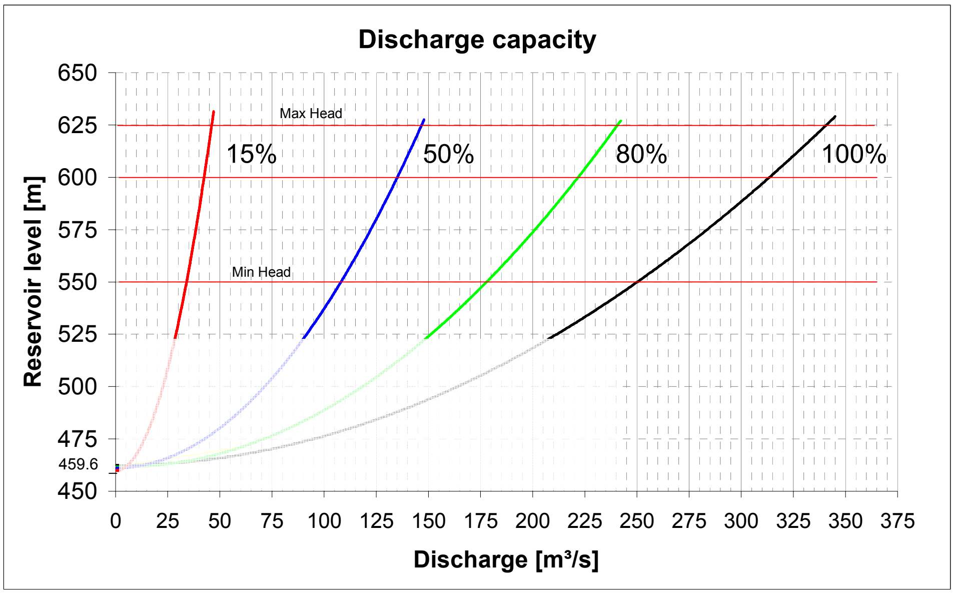


Figure 4. Bottom outlet discharge capacity

High-pressure section

Pressure head measurement in the area of the elliptical trumpet inlet showed the flow was clinging to the walls very satisfactorily, as manifested by a continuous pressure development (see Figure 5 below). There was no jet separation, and pressures were above atmospheric over the whole section down to the service gate. The maximum velocity in the rectangular cross section downstream from the elliptical transition was more than 47m/s. Figure 5 below is a graph showing hydraulic grade lines along the left-hand wall for the reservoir surface at top water level (T.W.L.) (625m above datum) and different gate openings. As already mentioned, all the pressures proved to be positive upstream from the service gate for all loading cases. Around the service gate and immediately below, the results varied around the reference level (level of measuring location).

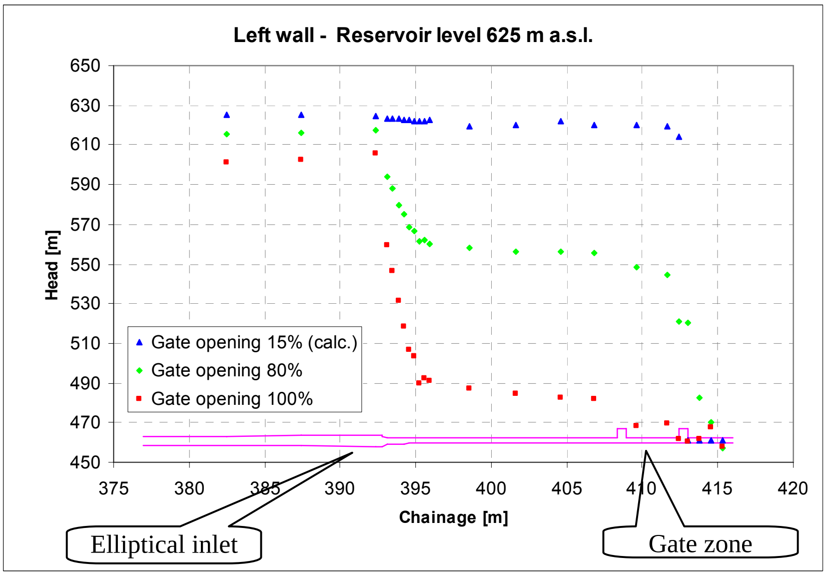


Figure 5. Hydraulic grade line for a full reservoir (625m above datum)

Free-flow section

Pressure head distribution in the free-flow section

Considering the extraordinarily high velocities as occur in the Kárahnjúkar bottom outlet, the pressures ought to remain in the positive range. This is why hydrostatic head was measured along the tunnel at the invert and the left-hand side wall 80cm above the invert. Figure 6 below shows, by way of example, the hydraulic grade line at the invert along the tunnel, for the reservoir surface at top water level 625m above datum and 100% gate opening. Note the distinct pressure drops at Aerators A, B and C. This is due to the fact that the water flow leaps over the aeration slots in the invert so as to produce subatmospheric pressure beneath the jet, which testified to the satisfactory performance of the aerators. The pressure peak downstream from Aerator A was caused by the fact that the jet impinged directly on the pressure tap The pressure variations at Stations 525, 640 or 715 can be explained by the presence of shock wave phenomena at the surface of the air-water mix.

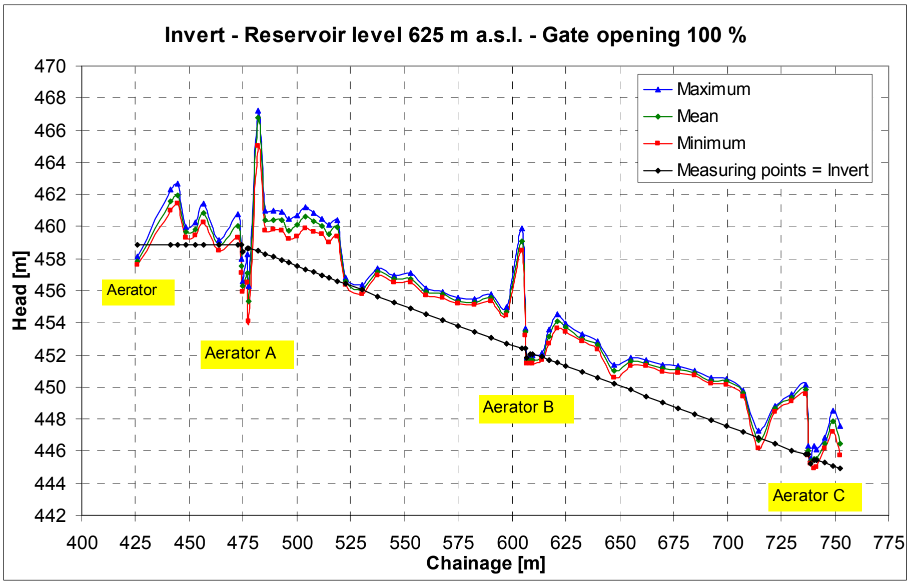


Figure 6. Hydraulic grade line at the invert of the free-flow tunnel, for a full reservoir (T.W.L. 625m above datum) and full gate opening

Figure 7 below is a graph showing the hydraulic grade line at the side walls, 80cm above the invert, for a full reservoir and full gate opening. The uppermost measuring locations gave subatmospheric pressures, which were due to the fact that the water had not yet reached the side walls. A distinct pressure rise was recorded at the fifth pressure tap (Station 441 metres). From this point the whole tunnel width filled with water. The pressure fluctuations around the aerators were a result of changes in geometry and width. A striking phenomenon was the occurrence of subatmospheric pressure directly below the aerator. This was found to be due to the fact that this was the point where the widened cross section contracted to the normal tunnel width and caused an angle in the vertical walls.

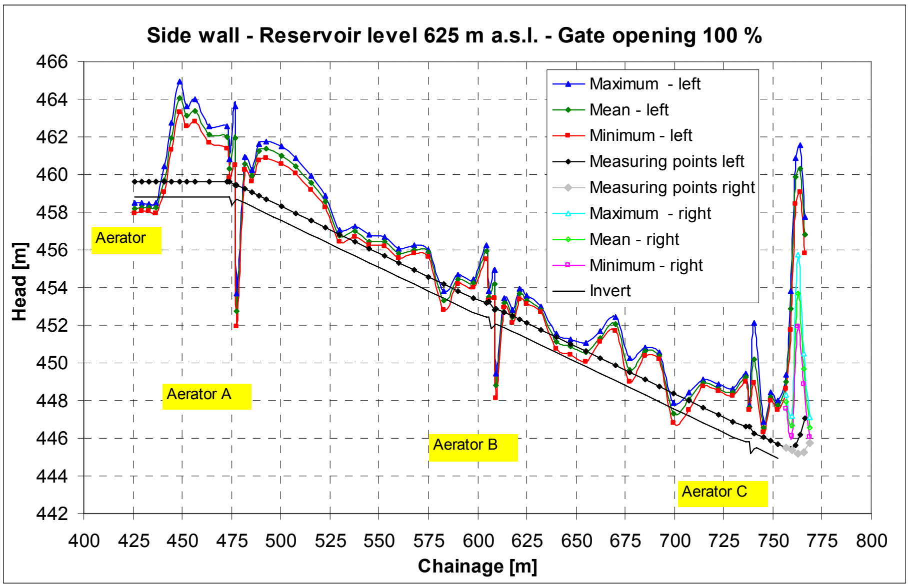


Figure 7. Hydraulic grade line at side walls of free-flow tunnel for a full reservoir (T.W.L. 625m above datum) and full gate opening

Pressure head variations not unlike those observed at the invert were seen to occur also at the side walls. These were caused by shock wave phenomena.

Flow conditions downstream from the gate chamber

The initial geometry reproduced in the model led to the development of rooster tails at the entrance to the free-flow tunnel. This was due to the tunnel widening suddenly from 2.55m to 5.2m three metres below the service gate, in combination with a 80cm step. The jet separated at that point, hit the invert at a distance of up to 15m further downstream, depending on flow rate and gate opening, then widened until reaching the side walls, partly climbing the side walls and, in the worst case, developing rooster tails up to the tunnel roof. This was aggravated by the fact that the slope angled from 0% to 5% about 60 metres downstream from the outlet into the free-surface tunnel. This implied the risk of rooster-tail developing with all its unforeseeable consequences. Figure 8 below demonstrates the rooster tails occurring with the reservoir at T.W.L. and full gate opening in the initial condition.

Figure 8. Rooster-tail development for a full reservoir (T.W.L. 625m above datum) and 100% gate opening, in the initial condition

Thus, several modifications were tested in the model in an effort to prevent rooster tails to develop after the jet impinged on the invert. The best variant resulting from the studies, and recommended for construction, included the installation of circular baffles on the original invert. Figure 9 below shows the flow behaviour at the same point as in Figure 8. The situation has substantially improved, as demonstrated by the disappearance of the rooster tails.

Figure 9: Flow behaviour for vertical baffles with invert remaining at the initial level, for a full reservoir (T.W.L. 625m above datum) and 100% gate opening (= final proposal)

Free-flow tunnel

As suggested by the results from the scale model tests, it may safely be assumed that the selected cross-sectional geometry will ensure that rooster tails and, hence, flow under pressure will not occur in the tunnel. The only exception is potential backwatering from the nearby spillway. This should be considered when selecting a suitable tunnel liner.

Air requirements

The high velocities within the free-flow tunnel hold the risk of local subatmospheric pressures, which in the worst case might cause cavitation damage. For this reason, three aerators were installed in the model in the invert immediately below the entrance to the free-flow section, as an addition to the initial aeration system. As modelling aeration may involve the risk of scale effects, it may be assumed that the air requirements measured in a model are at best equal to, but usually smaller than, the prototype value. The forces acting to supply air to the water-air mix are in fact reproduced smaller in the model whilst the surface tension, which counteracts air entrainment, is the same in model and prototype. This results in the air requirements being higher in the prototype, and this is a fact to be allowed for in the design of the aeration system for the prototype.

Defining the scale effect, N_a , as the relationship of prototype air requirements, β_N, to the air requirements determined from the model, β_M ($N_a = \beta_N / \beta_M$), the following equation after SAKHUJA et al. (1984) holds:

$$\log N_a = 0.0048 * (L_R - 1)$$

The selected scaling factor, L_R = 15, gives N_a = 1.17, thus suggesting that the air requirements in the prototype will be higher by about 15 to 20%.

The optimised baffles installed in the model to prevent the occurrence of rooster tails in the roof portion of the free-flow tunnel (see Section 3.3.2 above) had substantial effects on the air requirements. The measured rates of air flow (converted to prototype levels) are plotted against gate openings for different reservoir levels in Figure 10 below, which demonstrates the differences in air requirements between the initial condition and the baffle alternative, for equal water flow (gate opening) in the initial condition and with built-in baffles for gate openings greater than 50%. This may be explained by less air being entrained in the presence of the baffles, both through the resulting jet contraction and, especially, through the absence of rooster tails, which would entrain large air volumes. For the smaller gate openings, the air flows sucked in on the model remained fairly equal.

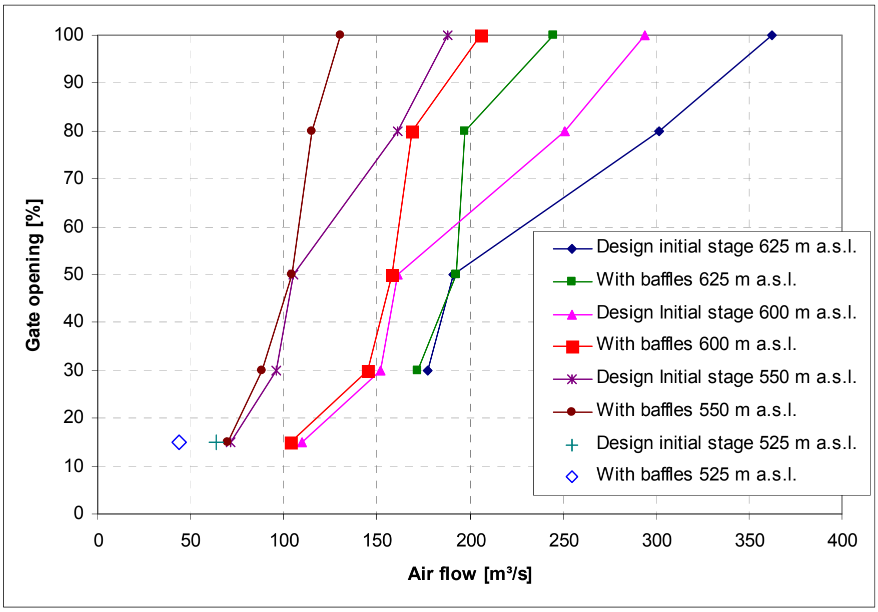


Figure 10. Measured air flow, converted to prototype conditions (initial state)

For the purpose of comparison, air intake to the tunnel was measured with no air being allowed to be blown out or sucked in through the tunnel portal. The results are plotted in Figure 11 below. Large flow rates proved to be associated with approximately constant rates of air flow sucked in. With smaller gate openings and, hence, lower flow rates, the closed portal gave a significant drop in air flow drawn into the tunnel. This is due to the fact that almost the whole air flow is entrained into the water during high rates of water discharge, no matter whether the tunnel portal is open or closed, while during lower discharges more air is sucked in through the air inlet than the jet is capable of entraining on its path through the tunnel. In other words, these loading cases showed air being blown out of the tunnel.

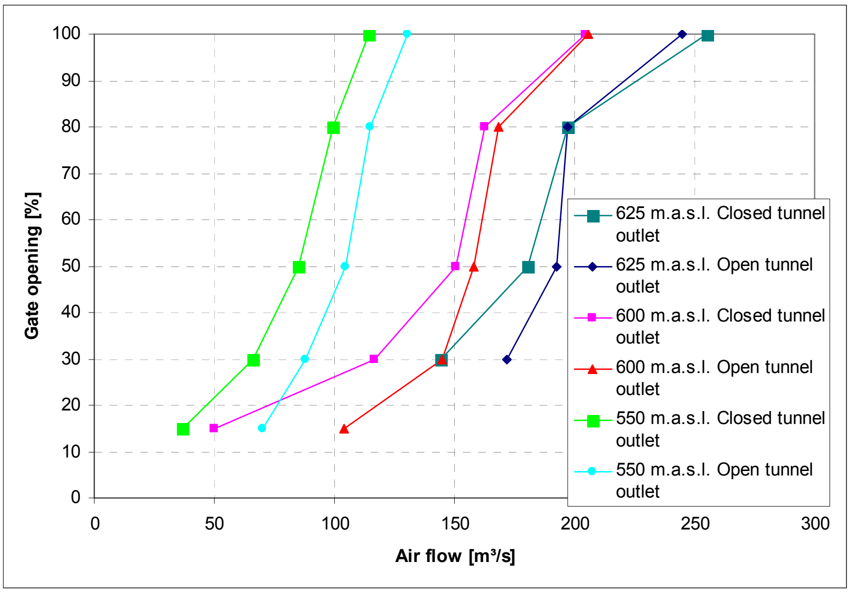


Figure 11. Comparative measurement with closed and open tunnel portal (air flows converted to prototype conditions)

The maximum air flow obtained with baffles installed and tunnel portal open was 244m³/s. The relationships of air flow to water flow (β value) measured were within the limits given in the relevant literature. It should, however, be pointed out that the air flows measured in the model were consumed along the whole tunnel length and not only at the entrance to the free-flow tunnel. The β value defined here thus includes the air intake at the aerators as well as the entrainment, release and re-entrainment of air along the tunnel. Figure 12 below shows the approaches by Sharma and USCE compared with the values measured with the reservoir full and various service-gate openings. A summary of air-entrainment calculations (Sharma, USCE, ….) is given in SPEERLI (1999).

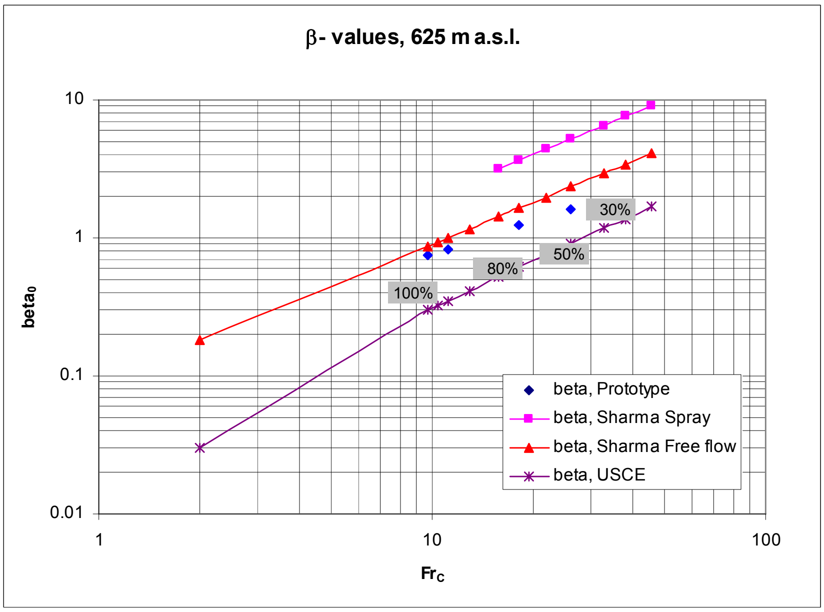


Figure 12. Theoretical β values and β values calculated for different gate openings

Flip bucket

The pressure measurements carried out in the flip-bucket area gave negative pressures neither on the left nor on the right side wall.

The jet is thrown into the gorge from a flip bucket provided at the end of the tunnel. As the bottom-outlet tunnel joins the canyon tangentially, so that the jet would hit the left canyon wall and, moreover, the geology of the project area gives reason to fear that parts of the canyon wall might break off and fall into the canyon, the client desired that a flip bucket should be provided to divert the jet further to the right and thus more towards the valley centreline. The impingement area of the jet proved favourable since it corresponded approximately to an ellipse oriented in the direction of the valley centreline.

The original flip-bucket design was modified to concentrate the jet and prevent potential pressure fluctuations by enlarging the radius of the right-hand side wall so as to contract the jet. Figure 13 depicts the jet with the reservoir surface at T.W.L. and for full gate opening. The left photo shows the initial condition, the right picture is a photo of the flip bucket after modification (Variant 1). Only a slight jet contraction on the right side was observed.

Figure 13. Flip bucket for a full reservoir (T.W.L. 625m above datum) and 100% gate opening; left: initial condition, right: Variant 1

As the scour hole was situated very close to the left canyon wall, the flip bucket was modified once more (Variant 2). The right side wall subsequently installed in the flip bucket was removed and a wall with a smaller radius was provided on the left side instead. This moved the outlet opening slightly to the right as compared with Variant 1, so as to divert the jet slightly more to the right. This made the jet practically clear the foot of the left slope, while placing the jet closer to the right canyon wall. The result of this variation, illustrated by Figure 14 below, corresponds to the final proposal.

Figure 14. Flip bucket for a full reservoir (T.W.L. 625m above datum) and 100% gate opening – final proposal (Variant 2)

Further data determined in the model were the throw distances and depths of the jet. The variants showed no major differences with respect to throw distance. The throw depths, however, were seen to increase in the variants, the largest depth being measured for Variant 2. This may be explained by the jet contraction in the flip bucket. The maximum throw distance measured was slightly above 100 metres, and the throw depth was 27 metres.

Downstream river bed

The hydraulic load caused scouring within a short time in the model. The scour location was dependent on flip bucket geometry, while scour depth varied according to the geological conditions and potential structural stabilisation. A scour hole, forming near a canyon wall, risks undercutting the slope, which in turn might cause rock portions to break off and fall into the canyon. Following a great number of model measurements for different flow rates, the shapes of the fully developed scour holes were surveyed for the above Variants 1 and 2. As mentioned in the preceding Section, the flip bucket of Variant 2 involved the best scour location, which developed slightly further to the right and thus towards the canyon centreline. This should minimise the undercutting risk for both canyon walls. Figure 15 below shows the scour pattern that developed for flip bucket Variant 2.

Figure 15: Scour pattern developing after operating flip bucket Variant 2 for a major length of time

Summary

This article has briefly outlined the results of 1:15 scale model tests performed for the Kárahnjúkar bottom outlet. The extraordinary dimensions of the structure posed special problems. In addition to determining discharge capacity, describing hydraulic grade lines in the high-pressure and free-flow sections, determining air entrainment in the model, the tests mainly aimed at studying flow conditions immediately downstream from the gate area, along the tunnel and in the flip bucket area. The model tests gave no pressure heads likely to constitute a potential risk in the prototype.

Installation of baffles modified the geometry of the uppermost section of the free-flow tunnel so as to avoid the development of rooster tails. Measurements and calculations permitted quantification – with all the uncertainties involved – of the expected air requirements in the prototype.

The flip bucket geometry was optimised so as to give only positive pressures and make the jet impinge at the best possible point in the canyon, where the scour hole would constitute the least risk.
These scale model tests included a large number of further studies which, exceeding the available space, cannot be discussed here. For greater details, refer to the client (see "Acknowledgements" below). (See also INSTITUT FÜR WASSERBAU, 2005)

Acknowledgements

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