Karahnjukar dam spillway: Comparison of operational data and results from hydraulic modelling

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The Karahnjukar dam spillway is the spillway for the Halslon reservoir, the main reservoir for the 690 MW Karahnjukar Hydroelectric Project in East Iceland. The spillway consist of a 140 m long overflowing weir with a capacity of 2250 m^3/s which discharges into a side channel, followed by a 450 m long chute. The chute terminates at a canyon edge where the jet drops some 100 m into a narrow gorge downstream of the Karahnjukar dam. During the design phase of the project, the flow conditions in the spillway were modelled in the hydraulic model tests in 1:45 scale model at the Laboratory for Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. The power plant went into operation in 2008 and since then considerable experience has been obtained from operation of the spillway. In particular, flow depths and air discharge measurements have been obtained during spilling periods. In this paper, these measurements are presented and compared with results from the hydraulic model tests. In particular, flow depths are discussed as well as aeration effectiveness.

1. Background

The 690 MW Karahnjukar Hydroelectric Project, which became operational in 2008 and is owned and operated by Landsvirkjun, the National Power Company of Iceland, is located in Eastern Iceland as shown in Fig. 1. Six 115 MW Francis turbines, operate under a gross head of about 600 m and maximum discharge of 144 m^3/s with an output of about 5000 GWh/a. The Halslon reservoir, the main reservoir for the project, is formed by three dams, including the Karahnjukar dam, Europe’s highest concrete faced rockfill dam with a maximum height of 198 m. The spillway for the Halslon reservoir consists of a side channel overflowing weir followed by a chute which terminates at a canyon edge where a jet falls some 100 m into a narrow gorge. The spillway design discharge is 1350 m^3/s whereas the Probable Maximum Flood (PMF) is 2250 m^3/s. A fuse plug, designed to pass catastrophic floods amounting some 6000 m^3/s, is located at the east end of the Desjara saddle dam.

The spillway facility consists of six main components: 1) a side channel, located parallel to the steep slope of the valley, at the west end of the Karahnjukar dam. It is designed as a compact component, with somewhat reduced width as the construction cost rapidly increases with channel width due to the steep valley slope. The weir has a crest length of 140 m; 2) about 300 m long and 17 m wide upper chute, extending from the side channel to an aerator; 3) a lower chute, about 115 m long, extending from the aerator almost to the canyon edge, expanding in width from 17 m to 30 m with baffles blocks at the downstream end; 4) a short lower platform, extending from the lower chute to the edge of the canyon; 5) a plunge pool in the canyon were the jet impinges the canyon floor; and 6) a tailwater dam that coupled with the plunge pool provides a water cushion for the jet. An overview of the spillway facility is shown in Fig. 2. For detailed description of each component, see Tomasson et al. (2006).

Fig. 1. Location of the Karahnjukar Hydroelectric Project.

The location and the layout of the spillway was dictated by environmental constraints and geological conditions requiring extensive measures in order to counteract the prevailing and in many respect difficult conditions. The resulting complex hydraulic design of the spillway and in particular the unique conditions and unconventional design required at the lower end of the chute where the jet plunges into the deep and narrow canyon at an oblique angle, necessitated a hydraulic model test following the preliminary design phase. Detailed discussion of the design solutions for the lower end and the canyon are in Gardarsson et al. (2009 and 2013) as well as in Berchtold and Pfister (2011). The spillway was designed to accommodate the design flood as well as the PMF flood. The design was tested and adjusted in a hydraulic model test at the Laboratory for Hydraulics, Hydrology and Glaciology of ETH Zurich. The scale of the hydraulic model was 1:45 (VAW 2006, Pfister et al. 2009).

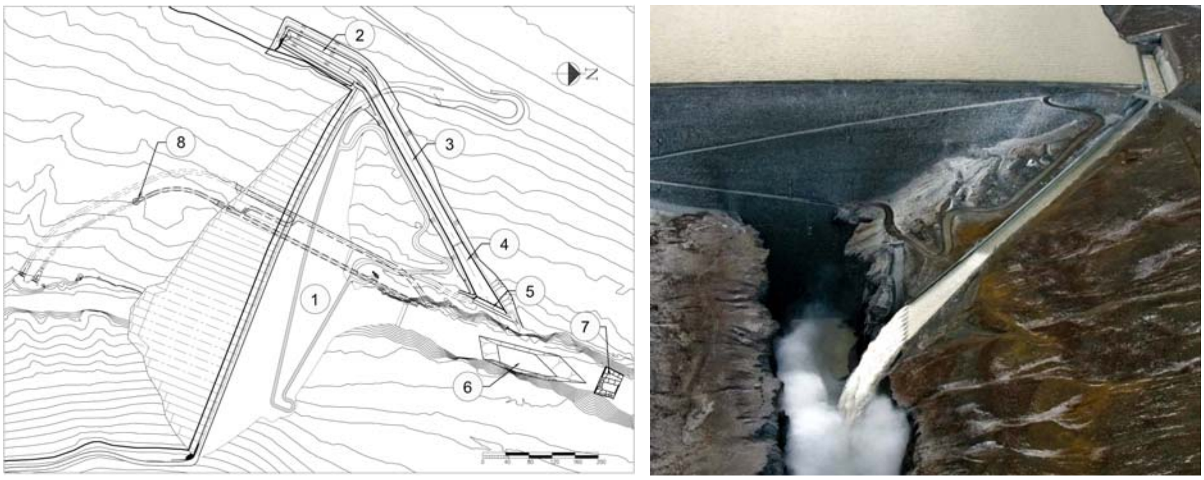

Fig. 2. Left: Layout of the Karahnjukar dam and Halslon reservoir spillway: (1) Karahnjukar dam; (2) Spillway side channel; (3) Upper chute; (4) Lower chute; (5) Lower platform; (6) Plunge pool; (7) Tailwater dam; (8) Bottom outlet; and diversion tunnels; Right: Aerial view of the Karahnjukar dam spillway during spill event.

2. Methods

The data were obtained by hydraulic model during the design phase and in the spillway during a spill period in 2010.

2.1 Hydraulic model measurements

The hydraulic model was built in the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich and the related works took two years altogether (VAW 2006). The model was operated under the Froude similitude with as scale factor of 1:45. It included an area of roughly 200 m times 250 m of the reservoir, the complete spillway, and some 500 m of the downstream canyon. Fig. 3 shows the upper and lower parts of the physical model.

The model study aimed to find a spillway geometry meeting the various requirements. To quantify the relevant hydraulic parameters, the extended test program included systematic (1) discharge measurements using MID, (2) velocity measurements using ADV and micro-propeller, (3) flow depth measurements using ultrasonic distance sensors and point gauges, (4) static pressure measurements using piezos, and (5) dynamic pressure measurements using transducers and transmitters with acquisition frequencies up to 1 kHz. Despite of the fact that the air entrainment at the aerator is not correctly represented in the model, the latter was implicitly derived by air velocity measurements in the air ducts with an anemometer. The flow pattern was documented and interpreted visually.

Fig. 3. Hydraulic model at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. Left: side channel; Right: jet impinging on plunge pool (Photos VAW).

2.2 Prototype measurements

The water depths in the side channel and the chute were obtained by painting gauges on the side walls with 5 cm spacing vertically aligned as shown in Fig. 4. The gauges were located at 11, one in the side channel and 10 in the chute, the upper most of those at station 365 m and the downstream most at station 20 m (the complete list of stations is shown in Table 1). Stations and datum are defined in accordance to the physical model for direct comparison of field data. Gauges are vertically aligned and station zero is at the downstream chute end. The gauge data was obtained by photographing each scale 5-10 times for a particular discharge and then the water elevation for each photograph was determined in post-processing. The average of the obtained values was then used as the measured value. It is noted that the water depth is measured at the left walls on site. In the hydraulic model, the water depth was measured at the chute centerline, and for significant discharges also along both sidewalls.

The aeration facility is located at station 150. It consists of a tower on each side of the chute (Fig. 5 shows the left tower and the aeration step) which draws in air through four pipes (diameter of each pipe is 0.8 m) due to the negative pressure nappe created downstream of the aerator. The latter consists of a step of height 0.4 m together with a 0.15 m high deflector, resulting in a total offset height of 0.55 m. The air velocity was measured with calibrated cup vanes in two of four pipes at the downstream end. Based on the measured velocity air mass flow was calculated. Other vital parameters necessary for air density calculations such as air temperature and atmospheric pressures, are obtained from a nearby metrological station. The local aerator air entrainment ratio is quantified by the air entrainment coefficient $\beta = Q_{air} / Q_{water}$ (Pfister and Hager, 2010a, b). The water discharge for the spillway was obtained from the official operational measurement equipment during the measurement periods.

Fig. 4. Left: Examples of the painted scales at each side of the aerator; Right: The left aeration tower. The air intake is at the bottom, fed by 4 0.8 m diameters pipes, and the 0.55 m step in the chute is clearly visible.

3. Results and discussion

3.1 Flow depths

Table 1 shows an example of the data obtained from the photographs of the gauges at the discharge 328 m^3/s. For each gauge, the average value is used as the water elevation measurement but the minimum and maximum water elevations were also recorded.

Fig. 5 shows the results for the side channel flow depths. The prototype and the model values originate from a location at 50 m weir crest length, measured from the left end of the weir when looking downstream over the weir, which is approximately in the middle of the side channel. The comparison shows that the average site depths was roughly 0.5 m above those from the model, representing a relative difference of some 10%. The site minima collapse well with the model data.

Fig. 6 shows the flow depths along the chute at different streamwise locations (Table 1), indicating the maximum, average and minimum site values as well as the model values. Note that location 365 m is just downstream of the side channel, the aerator is positioned at 125 m, and location 20 m is close to the chute end before the jet is issued.

For low discharges, the difference is within the measurement accuracy. For higher discharges, namely 200 to 400 m^3/s, the hydraulic model under-predicts the water elevation by about 10 and 20 cm, respectively, which corresponds to about 10 and 20%. The correlation between model and site values is thus a priori satisfactory.

There are multiple explanations for the slight underestimation of the flow depths. First, the visual observation cannot account for dynamic fluctuations of the flow surface, namely the rough flow surface with entrapped air transport. Second, the model values were derived along the chute centerline for discharges below 950 m^3/s (i.e. all compared discharges), and exclusively for large discharges also along the sidewalls. Given that there are shockwaves emerging at the side channel end and within the bend, these can significantly influence the transversal water level distribution. A third reason is the site flow depth variation between different measurements campaigns, that is, between different discharges. As an example, at station 190 m the water depth differ by 13 cm for only 29 m^3/s difference in discharge which reflects the uncertainty in the measurements. Finally, and most probable, the discrepancies between model and site flow depths relate to scale effects of the model linked to air-water two-phase flow. The Reynolds Re and Weber We numbers of the model flows are below limit values to avoid an underestimation of the model air transport (namely $Re=2.2\cdot10^5$ and $We^{0.5}=140$, Pfister and Chanson 2014), particularly for discharges below some 1'000 m^3/s. Using the average air concentrations according to Hager (1991) gives values of almost 20% on the upper part of the chute, and of some 22% downstream of the aerator. Adding this air to the model flow would result in more accurate flow depth predictions. This estimation and the prototype measurement in general, prove – vice versa – that the black-water flow depths (without entrained and entrapped air transport) are correctly represented in the model, as to expect under the Froude similitude (Pfister and Hager 2014). The locations 125 m and 110 m are in the direct influence reach of the aerator, and the difference in flow depths there is larger. This is again related to the underestimated air-water features of the physical model.

Table 1. Example of water level measurement data for the gauges for discharge of 328 m³/s.

Gauge	Station [m]	Measurements [m]	[m]	[m]	[m]	[m]	[m]	[m]	Average [m]	Min [m]	Max [m]
Gauge 1	20	0.7	0.9	0.9	0.7	0.7	0.6	nd	***0.75***	0.70	0.90
Gauge 2	60	1.4	1.0	0.9	1.0	0.8	1.1	1.1	***1.04***	0.80	1.40
Gauge 3	110	1.5	1.5	1.4	1.6	1.6	1.6	1.6	***1.54***	1.40	1.60
Gauge 4	125	1.4	1.4	1.3	1.3	1.1	1.5	1.0	***1.28***	1.00	1.45
Gauge 5	140	1.0	1.1	1.2	1.3	1.0	1.0	1.1	***1.09***	1.00	1.25
Gauge 6	190	1.3	1.1	1.2	1.0	1.0	1.0	1.1	***1.09***	1.00	1.25
Gauge 7	230	1.2	1.0	1.1	1.1	1.0	1.0	nd	***1.05***	0.95	1.20
Gauge 8	275	1.2	1.4	1.1	1.1	1.1	1.2	1.3	***1.16***	1.05	1.35
Gauge 9	325	1.3	1.3	1.4	1.3	1.2	1.3	1.3	***1.29***	1.20	1.35
Gauge 10	365	1.6	1.3	1.4	1.6	1.4	1.6	1.2	***1.42***	1.20	1.60
Gauge 11	Side canal	7.7	9.0	8.2	8.4	8.0	8.5	8.0	***8.26***	7.70	9.00

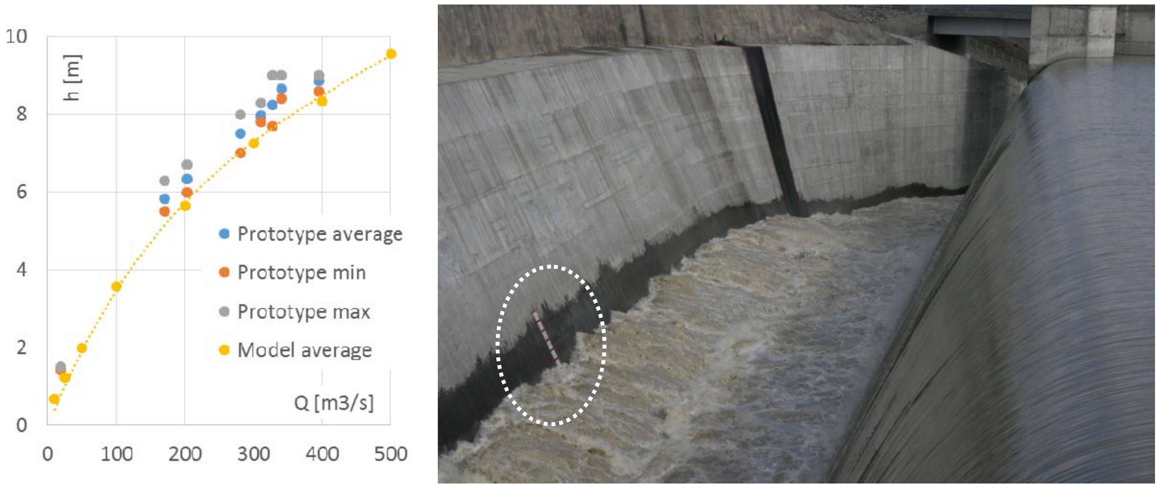

Fig. 5. Left: Comparison of measured water depths in the side channel; Right: location of gauge in the side channel.

3.2 Aerator performance

Fig. 7 shows the results for the measurements of the air entrainment during about 35 days. During the measurement period the water discharge ranged from roughly 50 m³/s to 450 m³/s and the air discharge ranged from about 80 m³/s to slightly less than 200 m³/s, resulting in β in the range of roughly 0.4 to about 1.1. The gaps in the data series are due to downtime in data logger power.

Fig. 8 shows all the data points of β as a function of the chute discharge. Additionally, the data of Guri with similar hydraulic conditions (Marcano and Castillejo, 1984), the prediction according to Pfister and Hager (2010a),

$$\beta = 0.0028\mathsf{F}^2\left[1+\mathsf{F}\tan\alpha\right]-0.1$$

and the physical model data are included. The Karahnjukar prototype data collapse well with the Guri prototype data, whereas prediction of Pfister and Hager (2010a) delivers some 60% of the effective value. As expected, the physical model drastically underestimates β.

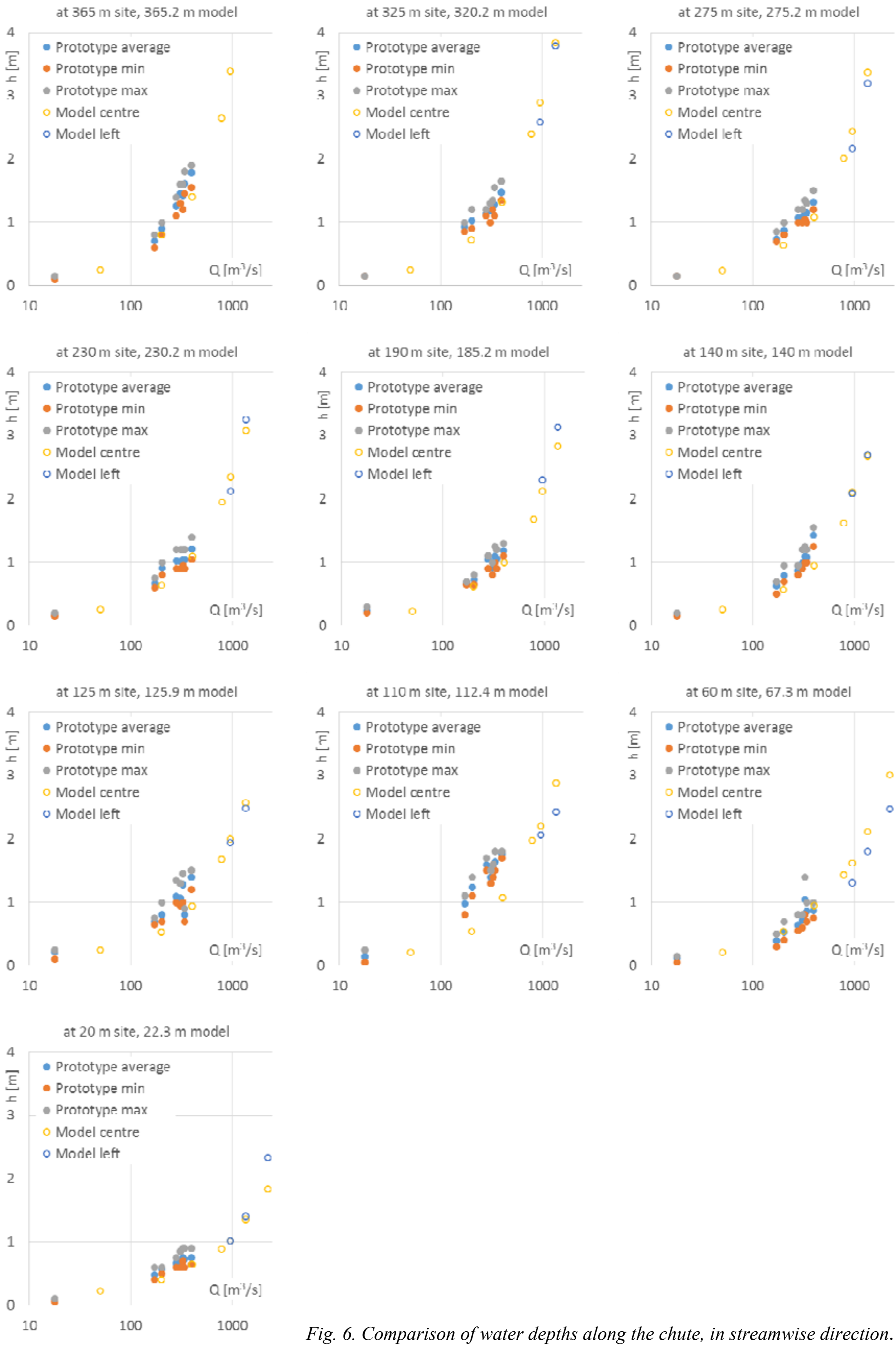

Fig. 6. Comparison of water depths along the chute, in streamwise direction.

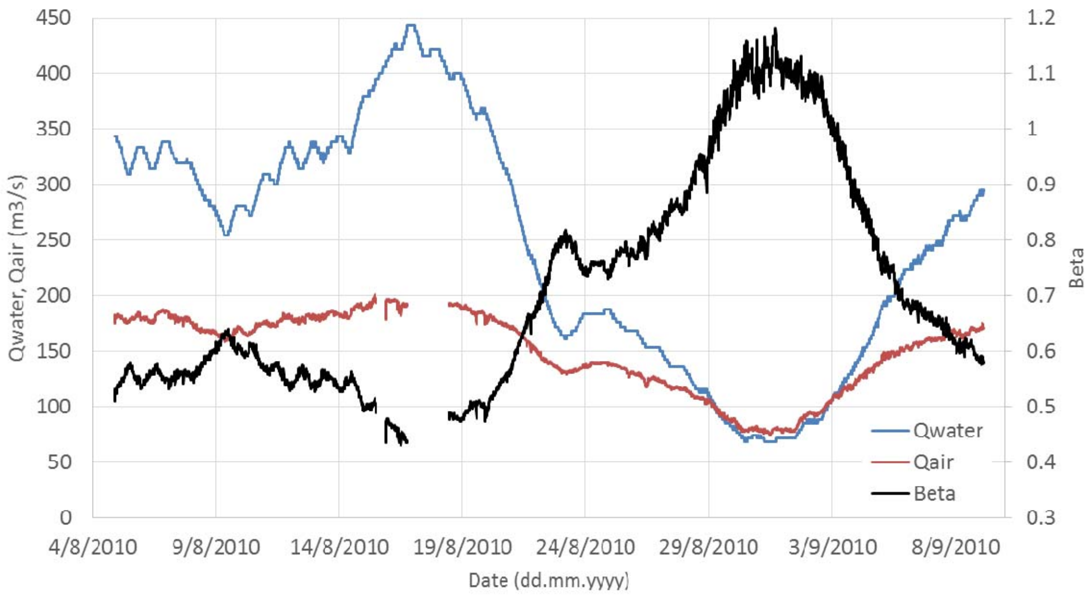

Fig. 7. Discharge (left axis), measured airflow (left axis), and the resulting air entrainment coefficient β (right axis).

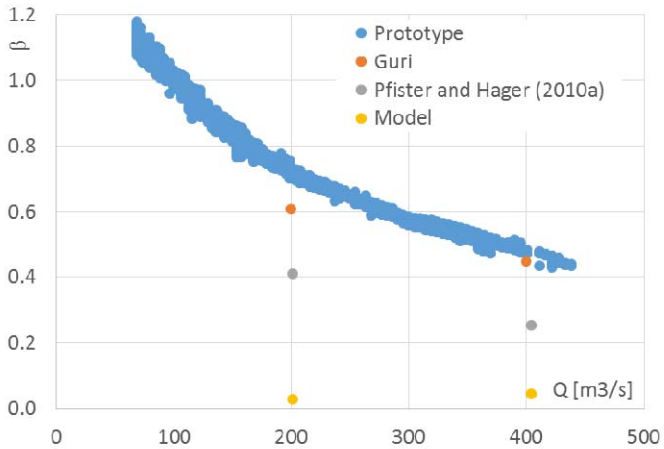

Fig. 8. β data as a function of the chute discharge.

The β values are further compared with other prototype measurements provided by Pinto (1991) (Foz do Areia, Emborcacao, Tarbela, Amaluza, Colbun), and by Marcano and Castillejo (1984) (Guri) in Fig. 9, with the prediction according to Pfister and Hager (2010a) as base. The figure shows that Karahnjukar behaves more efficient than the other considered spillway aerators (three points for discharges of 200, 300 and 400 m^3/s, with the Froude numbers from the physical model study), i.e. the prediction underestimates the effective values of β.

The layout and unit discharges of the Karahnjukar spillway are similar to Foz do Areia and Emborcacao. The differences relate to the inlet type (side channel versus gates), and to the chute length up to the first aerator (almost 300 m versus some 120 to 170 m). Consequently, the Karahnjukar flow includes eventually a higher turbulence at the aerator, originating from the side channel and particularly form the flow length. This could induce an enhanced aerator performance. Note that the minimum area of the air supply system relative to the chute width is around 0.19 m^2/m at Karahnjukar, being comparable with Emborcacao (0.22 m^2/m) and Foz do Areia (0.12 m^2/s).

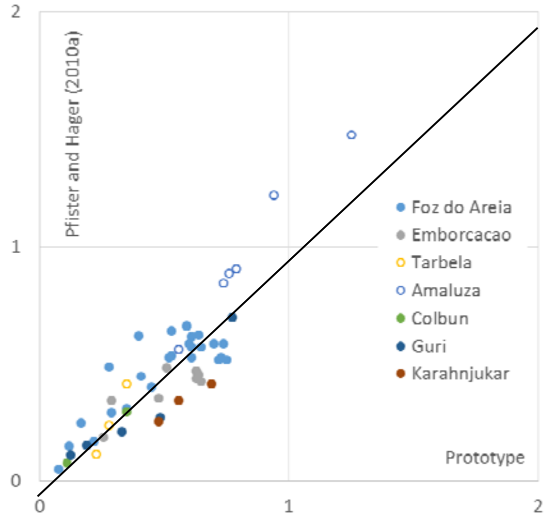

Fig. 9. Comparison of β for various prototypes with the prediction of Pfister and Hager (2010a).

4. Conclusion

Measured flow depths in the side channel and along the chute as well as the aerator air discharge for the Karahnjukar spillway during spill period were compared to data obtained from hydraulic models and literature.

The flow depths measured in the side channel in the Karahnjukar spillway during operation compare reasonably well to the water elevations predicted by the hydraulic model. The flow depths in the chute were slightly lower in the model than in the prototype in all cases, showing that the physical model underestimated the air transport. Correcting this deficit with values from literature results in a good agreement.

The aerator performance cannot be predicted with the current physical model, as expected. The model was set-up according to the Froude similitude allowing for a correct representation of inertia versus gravity forces, driving the drawdown curves correctly. However, turbulence and air features are systematically underestimated. The aerator performance was predicted from literature, including experience from other prototypes. For Karahnjukar, this approach led to the desired aerator operation regime.

Generally, physical models are reliable for the phenomena defined as relevant and the related dynamic similarity. This is confirmed by the herein described prototype measurements. Other phenomena like air transport, linked to other force ratios (including the viscous and surface tension forces versus inertia), are systematically subjected to scale effects and thus not represented correctly in the physical model. The error resulting from scale effects can be estimated with design equations provided in the literature.

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