IOP Conference Series: Earth and Environmental Science

Emergency gates - model scale tests at turbine runaway condition

To cite this article: M. Angulo *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **774** 012076

Emergency gates - model scale tests at turbine runaway condition

M. Angulo, A. Rivetti, L. Díaz, C. Lucino and S. Liscia

Laboratory of Hydromechanics, UNLP, 47 street Nº 200, 1900 La Plata, Argentina

E-mail: mauriangulo@gmail.com

Abstract. Emergency gates are the last link in the chain of safety of turbo-groups in case of distributor failure, safeguarding the power station from severe damage. These gates can be located at the turbine intake or at the outlet of the draft tube and can be controlled by gantry cranes or hoist hydraulic cylinders. Gates must descend with high flow for a short time to prevent the turbine from spinning at runaway velocity for periods longer than admissible, as that would entail the rise of uplift and downpull forces that may jeopardize their stability. Indeed, at the prototype scale, the closing maneuver entails a certain risk, because of which it is usually tested avoiding extreme conditions.

In this work, the operation of emergency gates was tested against more severe conditions on a reduced-scale physical model. The case study involves three emergency gates controlled by gantry cranes and located at the intake of a large Kaplan turbine which underwent high levels of vibration when operated at prototype scale.

Model tests were aimed at detecting and quantifying hydraulic phenomena that might emerge during operation with an eye on the proposal of alternative designs. Unlike most tests of this sort, the experimental setup includes the runner of the turbine assembled on a test rig, which allows for a more realistic flow distribution along the vanes during the gate closure under runaway conditions.

Steady state tests were carried out under runaway conditions, while stems of servomotors enabled the regulation of the position of the gate. Downpull forces were found to start at 12 % of the gate opening. Flow asymmetry was observed, gate on the left of the semi-spiral casing being the most affected by higher flow velocities. The runner vortex rope frequency was measured also at gate lip for some particular conditions.

1. Introduction

Given the risk they entail, runaway conditions are to be avoided, especially when operating at full head. Hydroelectric powerplants have thus to be provided with safety mechanisms of quick response that are able to protect the turbines by limiting their exposure to such flow conditions until their angular movement stops completely.

In case the primary shutdown system (i.e., distributor shutdown) fails, one emergency mechanism must be resorted to, namely shutting down a gate located either at the intake or at the draft tube of the turbine [1]. The forces that arise during the shutdown process and their oscillatory character are related mainly to the shape of the gate lip [4] and can be of such magnitude that might lead to the collapse of the gantry crane [1].

On field tests of gate operation under such emergency conditions are generally avoided. Furthermore, most studies (whether physical tests or numerical simulations) ignore the influence of the turbine operating at runaway conditions. Therefore, physical tests and numerical simulations could provide a valuable contribution to foresee the flow field under such complex conditions.

In this work, carried out under the framework of a project supported by the Yacyretá Binational Entity (EBY) and the National University of La Plata, Argentina (UNLP), we present the first data obtained from tests performed on a physical model of vertical lift gate upstream of a large-power, low-head turbine operating under runaway conditions.

The case study concerns the Yacyretá 20-turbine hydroelectric powerplant, which is provided with a gantry crane for the operation of three lift gates, one for each of the vanes of the intake (Fig. 1). Shutdown proceeds under controlled conditions over a period of approximately eight minutes. The gates have an upstream seal and the dimensions in meter are 18.4 * 8.2 * 9.31, and a weight of 135 tons.

The turbines are Kaplan with five blades and a 9.5 m runner. The capacity is 155 MW, the nominal head and flow are 22.7 m and 780 m³/s, respectively. The rotational velocity of the turbine is 71.42 rpm.

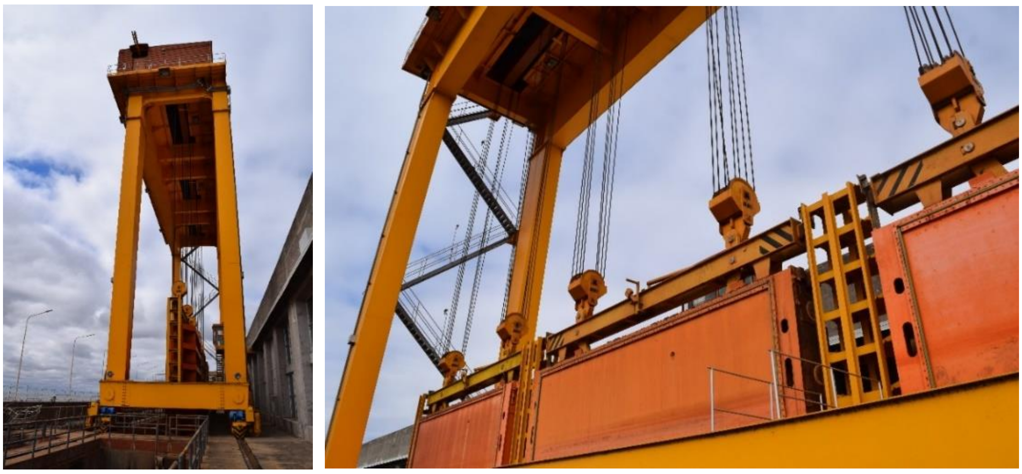

Figure 1: Front and side view of the gantry crane holding the intake emergency gates.

2. Methods and materials

2.1. Physical model

2.1.1 Test stand

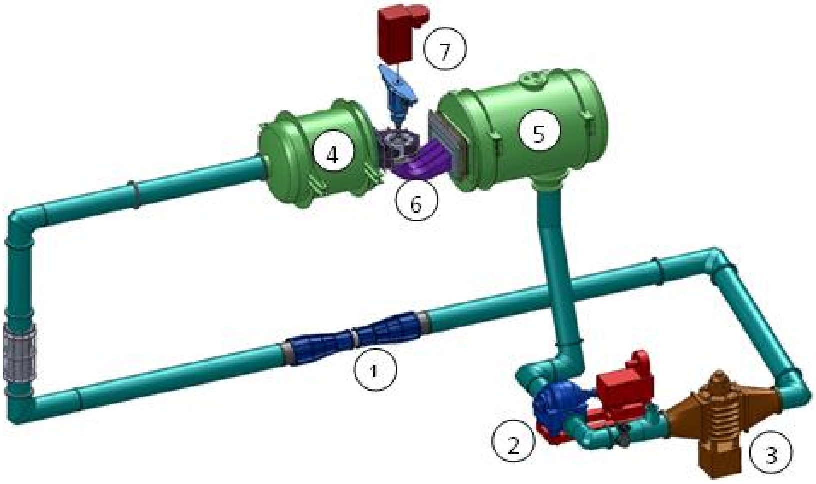

Figure 2: Test rig facility at the Laboratory of Hydromechanics of La Plata, Argentina. (1) Venturi flow-meter; (2) Recirculation pump; (3) Dissipation valve; (4) High-pressure tank; (5) Low-pressure tank; (6) Model scale; (7) Motor-generator.

Experiments were performed at the Laboratory of Hydromechanics of the National University of La Plata, Argentina. The test rig is a closed circuit that allows for the testing of Kaplan and Francis turbines (Fig. 2). The experimental setup followed the IEC60193 standard [5] and concerned a scale model of a 5-blade Kaplan turbine with 24 stay and guide vanes with a diameter of 340 mm (scale 1:27.94) and specific speed of 614 in metric units.

2.1.2 Gate.

The physical model, which consists of three lift gates motorized in such way that can shut independently of each other, allows for both static and dynamic tests. Properly instrumented, forces exerted on the surface of the gates can be calculated by means of integration of pressure measurements. Pressure-sensor data are also subjected to signal processing techniques for the characterization of the oscillatory tendencies both in time and in the frequency field.

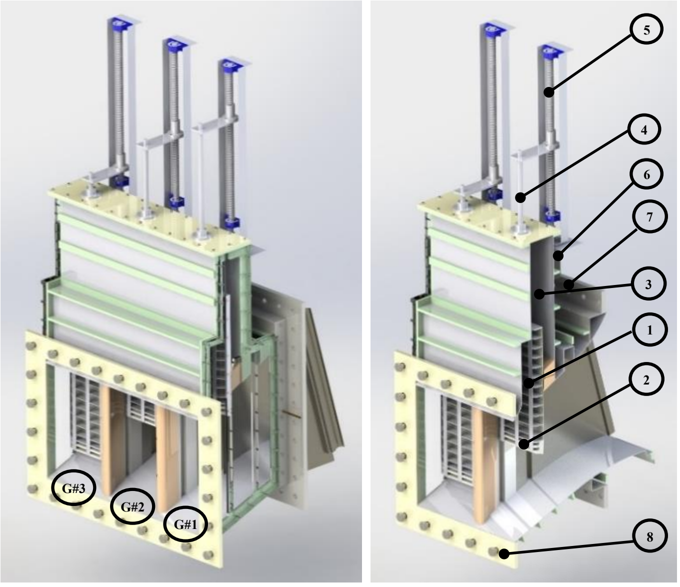

Figure 3.- a) Back view of the physical model. b) Cross section of the intake. 1) Emergency gate, 2) Gate lip, 3) Gate chamber, 4) Gate stem, 5) ACME screw, 6) Servomotor to control opening, 7) Connection flange to high pressure tank, 8) Connection flange to low pressure tank.

Figure 4. Intake with emergency gates of a Kaplan turbine as mounted on the test rig.

2.1.3 Equipment.

Pressure transducers were installed on both the upstream and downstream sides of the upper part of the gate and along the bottom lip (Fig. 5). It is worth pointing out that most similar tests reported in the literature have been performed on gates whose lips form a positive angle with the upstream direction [6]. Besides, a hydrophone was installed at the intake floor 54 mm downstream the closure section at the center of G#3. The acquisition frequency was 500 Hz.

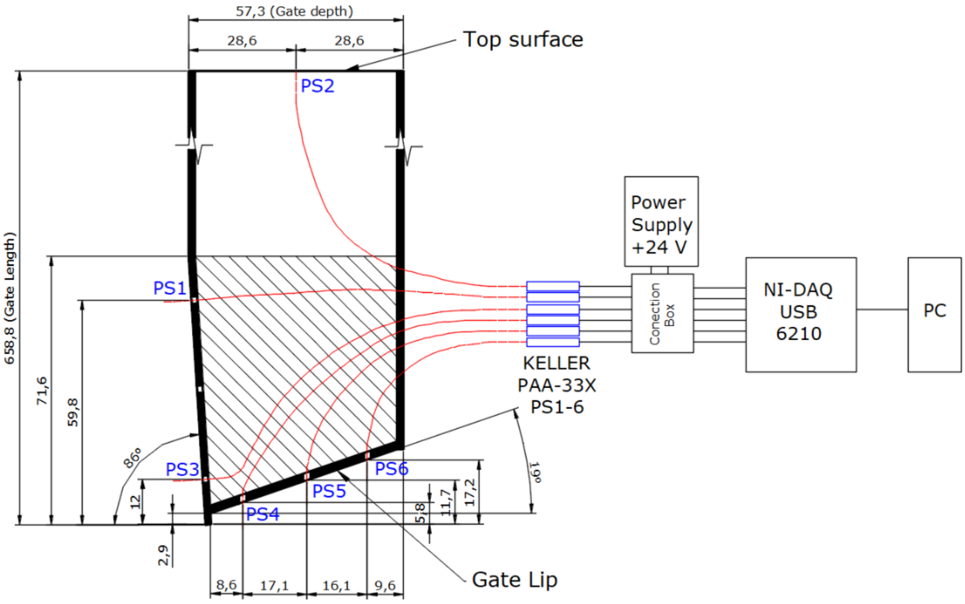

Figure 5. Cross section of model scale gate showing the position of pressure sensors and the measurement chain. The gate dimensions in millimeters are 658.8 * 333.2 * 57.3 (L * w * d) and each channel is 293.5 mm width.

Table 1. Instrumental.

Instrument	Nomenclature	Characteristics	Prototype
Pressure sensor	PS1	Brand	Keller
	PS2	Model	PAA – 33X
	PS3	Type	Piezoresistive
	PS4	Range	0-3 bar abs
	PS5	Output rate	400 Hz
	PS6	Accuracy	0.01 FS
Hydrophone	HID	Brand	Bruel & Kjaer
		Model	8103-D-200
		Position	Floor downstream gate
		DA frequency	500 Hz

2.1.4 Boundary conditions and Test procedure.

The model was tested at Froude similarity. The main boundary condition is to keep constant turbine head (H_m) for a given reservoir level fixed at the normal head water (N_{HW}). The runner and the guide vanes opening were set for off-cam condition of maximum flow at runaway. At this point the main torque (T_m) is zero as it is linked and controlled by the generator. Another condition was tested that consist in disconnecting the runner shaft from the generator, so the runner is free to rotate (FR).

Then tests consisted on setting different steps of gate opening (y) for the three gates, from the maximum to a minimum near to close position (0.5 %). For each step the flow passing through the gates is a consequence of setting Tm= 0 Nm, for the case of free runner the flow increases up to 13% for the full open condition. Also some tests were done with a vertical shift of 100 mm between contiguous gates.

On each test, pressures were measured for G#1 and G#3, also hydrophone at vane #3. All state variables related to the turbine: H_m, Q_m, n_m, were recorded.

Table 2. Tests. The main torque column indicates if the generator is connected to the runner shaft or it is free to rotate (FR). The gates closure tells about if all the gates close at same opening or if one is lower than the others. Gate opening column list the number of points for each test.

Test #	Type	Main Torque	Gates closure	Gate openings #
1	Steady State	FR	G#1=G#2=G#3	18
2		0		18
3		FR	G#1 first	8
4		FR	G#3 first	8

3. Results

3.1 Downpull coefficient.

Studies are focused on hydraulic forces hence, friction and gravity forces acting on the gate are not addressed here. The force balance assumes the gate as a “closed box”, so to calculate gate downpull it is usual to use the equation [1]. The downpull coefficient K is unknown and depends on the gate lip geometry. As it was mentioned, it was only possible to find references of gate lips with a positive angle in the upstream direction [1, 2, 3, 4, 7, 8, 9, 10, 11] but only one reference with an angle in the downstream direction [6]. Our case study has to angles, 86° in the upstream direction and 19° in the downstream direction (Fig. 5). Sund, et al [6] modeled with CFD a similar profile for three angles; from these results it was calculated K and compared with our measurements (Fig. 6).

$$K = \frac{D_p}{\gamma\, A\, H} \quad [1] \qquad\qquad D_p = F_B - F_T - F_{Gw} \quad [2]$$

Where:
K: Downpull coefficient. Positive values indicate downpull, negatives indicate uplift forces.
D_P: Downpull force, calculated as in Equation [2]. If flow is zero then, $F_B - F_T = F_{Gw}$ and $D_p = 0$
γ: Density of water.
A: Area of the horizontal projection of gate (w * d).
H: Operation head measured from the reservoir level to the closure plane of gate.
F_B: Force applied at the bottom of gate.
F_T: Force applied at the top of gate.
F_{Gw}: Buoyant force.

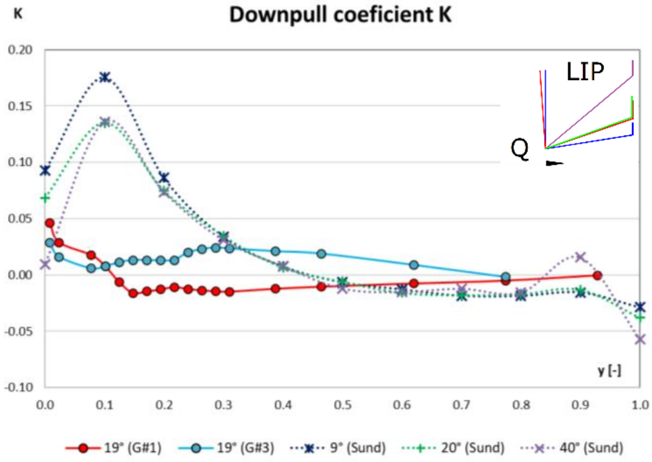

Figure 6. Downpull coefficient vs. gate opening (y) for gates #1 and #3 for free runner condition, compared with profiles studied by Sund, et al. For close position y = 0, for totally open y = 1.

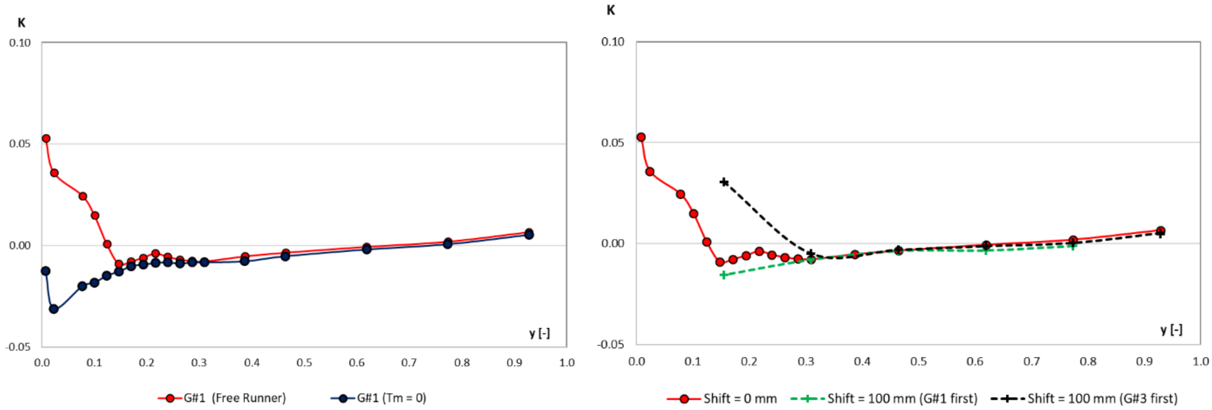

Figure 7. Downpull coefficient vs. gate opening. On the left, curves show the variation of K depending on the condition of runner rotation, free or runaway. On the right, curves show if the 3 gates close at same opening or if there is a shift, also indicates which gate is lowering first.

3.2 Frequency domain

Dynamic measurements of pressure were done. For each pressure signal and the hydrophone FFT was calculated. On tests where the runner is disconnected from de generator, it was detected a peak frequency as the gate close from 3 to 1.7 Hz in all the pressure sensors and the hydrophone (Fig 8, Graf y-f). However, this peak it is not detected when testing for Tm = 0. Records of the velocity of the runner and a pressure transducer connected to the draft tube cone, permitted the detection of a vortex rope spinning at a frequency of $0.277 * f_n$ in coincidence with the peak present at the gates lips.

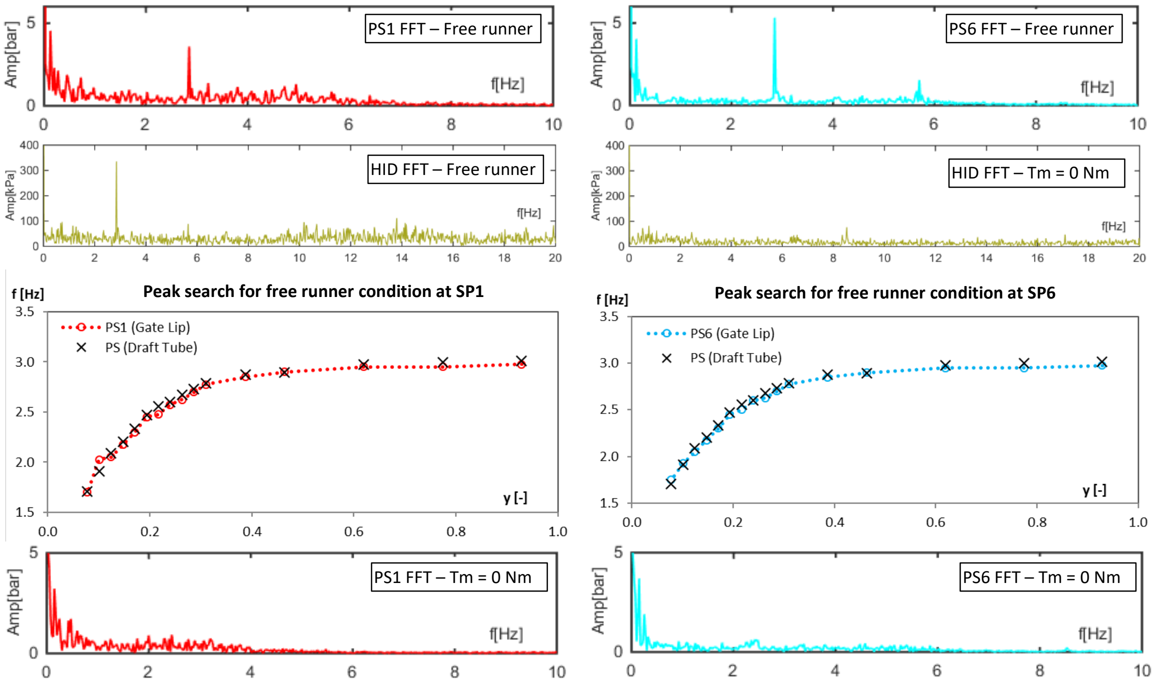

Figure 8. Dynamic measurements. PS1 (red), PS6 (cyan) and hydrophone (golden). Spectrums for the signals are shown for the case of free runner and Tm = 0 (runaway). Comparison of peak frequency between pressure the sensors at gate and at the draft tube cone is indicated as a function of gate opening (y).

4. Discussion

In this work a series steady state tests were performed on a physical model of an emergency gate at the intake of Kaplan turbine. These test are normally done without connecting the scale model of the turbine downstream. This implies that flow and level downstream the gate are regulated with a valve but it has no influence with the turbine operation. Besides, this studies do not take into account the flow distribution between vanes discharging into the semi-spiral casing. For all of these reasons tests were done with the complete turbine, so for each opening step, flow is automatically regulated if the reservoir level and head are kept constant and the runner is at runaway speed, that is main to set torque equal to zero. Then the flow distribution between channels is more realistic.

Measurements of dynamic pressures where done for gate #1 (right bank) and gate #3 (left bank) on the lip and the top surface of the gate. By means of the pressure distribution method, hydrodynamic forces acting on the gate could be calculated, to determine whether there is an uplift or downpull force during the gate closure.

For the lip geometry of the case study it was calculated the downpull coefficient K. It is important to say that few references were found, with the exception of Sund [6], that has a bottom angle in the downstream direction. A comparison for different angles is shown at Fig. 6. For the gate #1 there is a very little uplift force acting between 12-50 % of opening, for the rest there a downpull force acting on it, but for the gate #3 only a downpull force is acting for all the closure positions. Sund, simulated by means of CFD, profiles that display the same tendency where an uplift force is present from 50-100% and a downpull force has a peak at 10 %. Our case study has a downstream angle of 19° very near the 20° of Sund, but the upstream angle is 86° while the rest are 90°, moreover the gate studied has a sharp cut-off plane. These differences of the profile geometry change drastically the coefficient K tendency within the range of 0 to 30 % of the gate opening.

As the emergency gates acts when turbine is at runaway speed, the turbine model was set for zero torque for each opening step. But with the eye on performing dynamic test on gate, we disconnect the runner from the generator, so it is free to rotate, which increase the flow compared to the runaway speed at a maximum of 13 %. This situation it is not so unreal if it is considered that on prototype the turbine is connected to the generator; in consequence when turbine goes to runaway speed there is a frictional torque due to guide and thrust bearing which is a situation in between zero torque and free runner. In Fig. 7(left) it can be seen that forces changed to uplift direction.

Another aspect analyzed is the possibility that gates are descended simultaneously, but with a shift between them, e.g. gate #1 is 2 m lower than gate # 2 and 4 m lower than gate # 3. As it is shown in Fig. 7(right) when gate # 3 is lower than # 1, the downpull on gate # 1 increase at the opening of 30 % while in the case of same opening for all the gates the downpull starts later, near a 12 %. This is important because operational manuals in this power station indicates a shift between gates, but there is no good reason for that. The difference of results could be due to a change in the distribution of flow between gates.

A final point that was studied is related with the fact that there is a turbine spinning at runaway downstream the gate and how it can affect the gate closure. As we could measure, when testing for free runner condition a peak frequency coming from the runner chamber in coincidence with a vortex rope was detected (Fig 8). This was not found for the condition of $T_m = 0$ however, as it was said previously, the prototype real situation is an intermediate between them. If we had tested without the turbine, we would never have worried about this low frequency but it should be considered to study the gate vibrations.

5. Conclusions

A different lip gate profile witch cannot be found on records was tested. The design shown a flat tendency of the downpull coefficient for all gate openings compared with references. Therefore, it can provide a more stable distribution of downpull-uplift forces.

Another aspect, is that the emergency gate design was tested including the complete turbine. This is not the standard practice for testing gates due to the complexity that installing the whole machine involves. Results suggests that to analyze forces acting on gates, the flow distribution between gates it is not so critical, but it could be a good practice to take it into account adding part of the spiral case.

Also when testing without the turbine, it is recommended to analyze the influence on gate vibrations due to the frequency of vortex rope formation downstream the runner. Moreover, zero torque and free runner tests shown that it will affect downpull coefficient distribution due to an increment of flow through gates. Then, an increment of the design flow should be test to check if the K coefficient is affected to consider a more realistic simulation of runaway condition when testing without the turbine.

More work need to done related to dynamic test for a series of closure velocities and to analyze the influence of the inertia or the turbine-generator group on downpull forces.

Acknowledgement

The authors would like to thanks to the technical director of the Yacyretá power station, Eng. Marcelo Cardinalli, for conceding permission to publish this work.

References

[1] Erbisti O 2014 *Design of Hydraulic Gates* (London: Taylor & Francis Group)
[2] Naudascher E 1991 *Hydrodynamic Forces* (Rotterdam: A.A. Balkema)
[3] Naudascher E, Rockwell D 1994 Flow-induced vibrations (Rotterdam: A.A. Balkema)
[4] Lewin J 2001 *Hydraulic Gates and Valves – In Free Surface Flow and Submerged Outlets* (Londres: Thomas Telford Ltd, London)

[5] IEC standars 1999 *Hydraulic Turbines, Storage Pumps and Pump-Turbines-Model Acceptance Tests*; IEC60193

[6] Sund M, Magnusson F 2014 Numerical study on hydraulic vertical lift gate during shutdown process (Sweden: KTH Royal Institute of Technology School of Engineering Sciences) DiVA, id: diva2:1087251

[7] Ismail Aydin, Ilker T. Telci & Onur Dundar (2006) Prediction of downpull on closing high head gates, Journal of Hydraulic Research, 44:6, 822-831, DOI: 10.1080/00221686.2006.9521733

[8] Göbel G, Gebhardt M, Deutscher M, Metz W, Thorenz C 2019 *Numerical simulation of flow-induced vibration on gates with underflow* proceedings of the 38th IAHR World Congress September 1-6, 2019, Panama City, Panama

[9] Khosrojerdi A 2012 *Hydraulic studies of pressure distribution around vertical lift gates* Indian Journal of Science and Technology Vol 5 no 3 Mar2012 ISSN: 0974-6846 pages 2268-2272

[10] Kolkman P, Jongeling T 2007 Dynamic behaviour of hydraulic structures Part A Structures in flowing fluid Part C Calculation methods and experimental investigations Delft hydraulics

[11] Predina A, Klasincb R 2000 *Emergency gate vibration of the pipe-turbine* Shock and Vibration 7 (2000) 3–13 ISSN 1070-9622, IOS Press

[12] Rennó J, Antunes G 2017 *Batalha hpp roller gate cfd vibration diagnosis* American Journal of Hydropower, Water and Environment Systems Vol 4 ISSN 2317-126X pp 6-10