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Grand Ethiopian Renaissance Dam: Stepped spillway performance under heavy operation

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1 INTRODUCTION

The Grand Ethiopian Renaissance Dam (GERD) project along the Blue Nile River is located 700 km NE of Addis Abeba (Ethiopia). The Ethiopian Electric Power company (EEP) is the employer, WEBUILD S.p.A. the EPC Contractor, and Studio Pietrangeli Srl the designer. The hydropower plant is almost completed and is producing energy since 2022.

The project includes a roller compacted concrete (RCC) Main Dam (175m high, 10.2 Mm^3) and a concrete faced rockfill (CFRD) Saddle Dam (60 m high, 5 km long, 17 Mm^3). The 5,150 MW installed power will be generated by 13 Francis turbines in two outdoor power houses located at the Main Dam toe on the right and left riverside. The project also includes 9 bays' gated spillway, 1 ungated auxiliary spillway, an emergency spillway and 2 middle outlets to allow the control of the reservoir impounding. When completed at its full capacity, the GERD will feature the largest dam in Africa.

The GERD has recently been defined as iconic project (IWPDC May 2024) due to its peculiar characteristics. Historically, it has been referenced in texts from the 1st century AD; economically, it has a significant impact on the Ethiopian economy that justified its name; technically, it contains innovative solutions and finally politically, requiring efforts for cooperation in the governance of the transboundary Nile River waters and their benefits sharing.

The civil works of hydropower plant are completed whereas erection and come into operation of the generating units is in progress. The Plant is producing energy with two units since 2022.

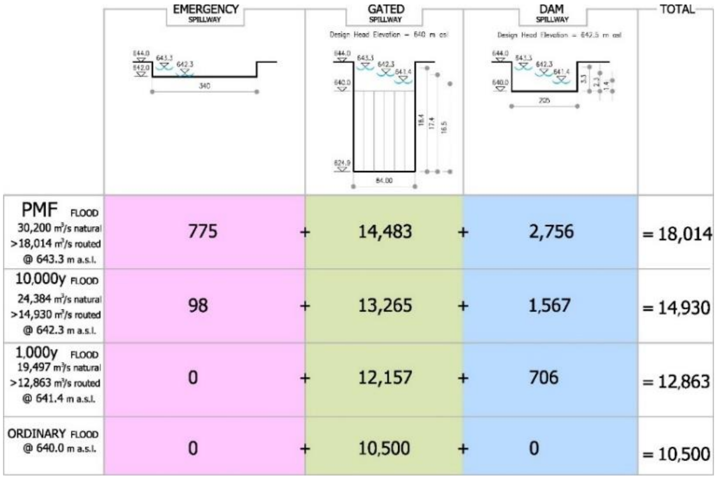
This paper is focused on the behavior of the temporary stepped spillway designed to manage the discharge of the large river flows during the impounding stages, and particularly on the comparison between observations and prototype measurements made during the heavy operation.

Figure 1. GERD Main Dam and powerhouses, downstream view

2 GERD SPILLWAY SYSTEM

The GERD Hydroelectric Project relies on three different spillways to guarantee the controlled release of floods, i.e.,

- A Gated spillway located on the saddle between two hills on the left bank of the Blue-Nile,
- An Auxiliary ungated stepped spillway located on the central portion of the main dam,
- An Emergency ungated side-channel spillway located on the right abutment of the 'saddle dam'.



	EMERGENCY SPILLWAY		GATED SPILLWAY		DAM SPILLWAY	TOTAL
PMF FLOOD 30,200 m³/s natural >18,014 m³/s routed @ 643.3 m a.s.l.	775	+	14,483	+	2,756	= 18,014
10,000y FLOOD 24,384 m³/s natural >14,930 m³/s routed @ 642.3 m a.s.l.	98	+	13,265	+	1,567	= 14,930
1,000y FLOOD 19,497 m³/s natural >12,863 m³/s routed @ 641.4 m a.s.l.	0	+	12,157	+	706	= 12,863
ORDINARY FLOOD @ 640.0 m a.s.l.	0	+	10,500	+	0	= 10,500

Figure 2. GERD permanent spillway system and flow sketch

2.1 *Auxiliary Stepped Spillway Characteristics*

The auxiliary spillway, located in the central portion of the dam, is characterized by a 205 m long (net) ogee sill at elevation 640 m asl capable of discharging up to 2800 m^3/s in case of extreme flood events. Two different slopes characterize the upper and lower portion of the chute as detailed in the following table and figure.

Table 1 – Main Characteristics of crest and stepped chute

	Upper Portion (640.0-553.4 m asl)	Lower Portion (553.4-497.4 m asl)
Total chute width (m)	275	275
Chute slope H:V	0.77 : 1	0.95 : 1
Step height (m)	1.2	1.6

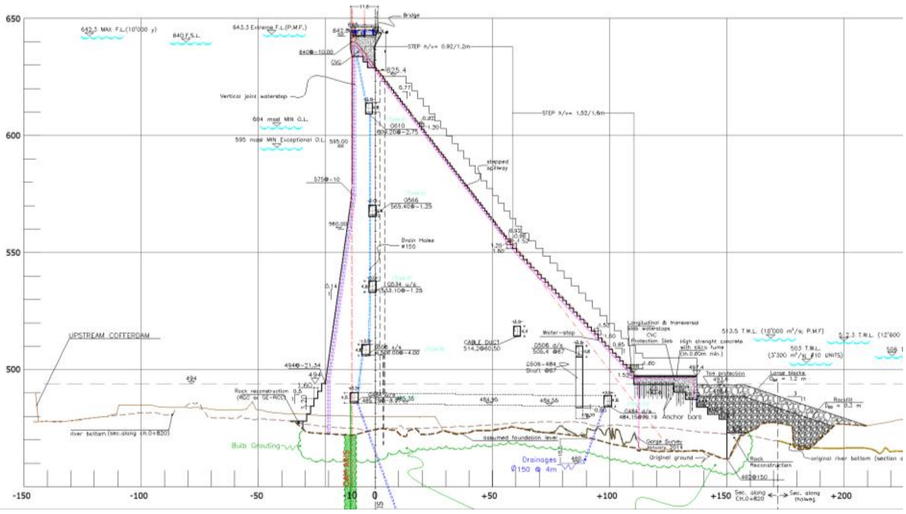


Figure 3 – GERD, Permanent stepped spillway typical cross section.

2.2 *Temporary Stepped Spillway layout*

A “Low Block” in the central portion of the dam was foreseen to guarantee the controlled dam overtopping during construction phases. In-fact, overtopping occurred during the past 7 years (2017-2023) at five different levels - namely 525, 560, 575, 600 and 620 m asl - with the hydraulic head ranging from 25 to 120 m. The "Low Block" width, originally of 120 m, was extended to 260 m above elevation 525 m asl to limit the specific flow at higher heads. The dam is going to be completed this year at the full storage level 640 m asl and no additional temporary operation of the stepped spillway is envisaged for the future.

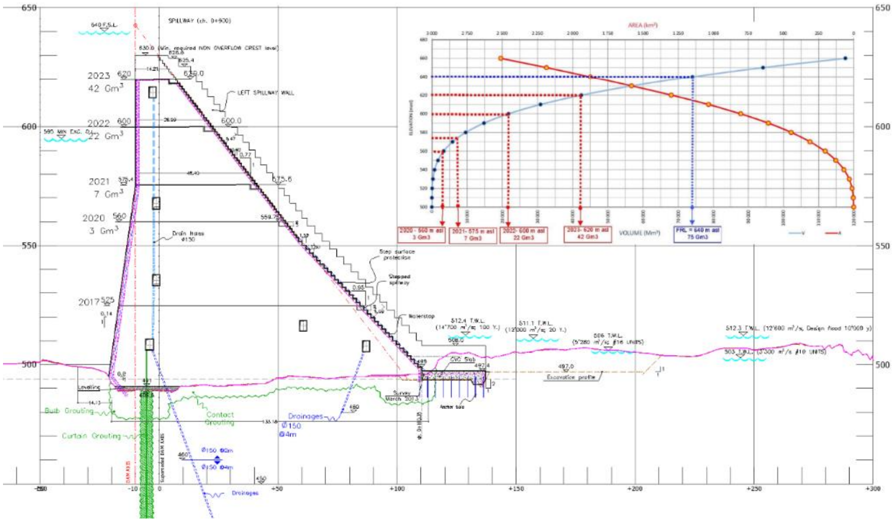


Figure 4 – GERD, Temporary stepped spillway, Overtopped Low block stages during impounding stages

2.3 *Heavy duty Operation*

Every year a huge volume was discharged through the "Low Block", ranging from 12,800 Mm^3 to 66,000 Mm^3, in the years 2023 and 2020 respectively. The maximum specific discharges were reached in 2019, i.e. 59 m^2/s (with a 120 m wide sill at elevation 525 m asl) and in 2020, i.e. 44 m^2/s (with a 260 m wide sill at elevation 560 m asl). The following figure provides plots of the specific discharged-flows and duration curve for four (2017 – 2020) out of the seven years of temporary operation of the stepped spillway.

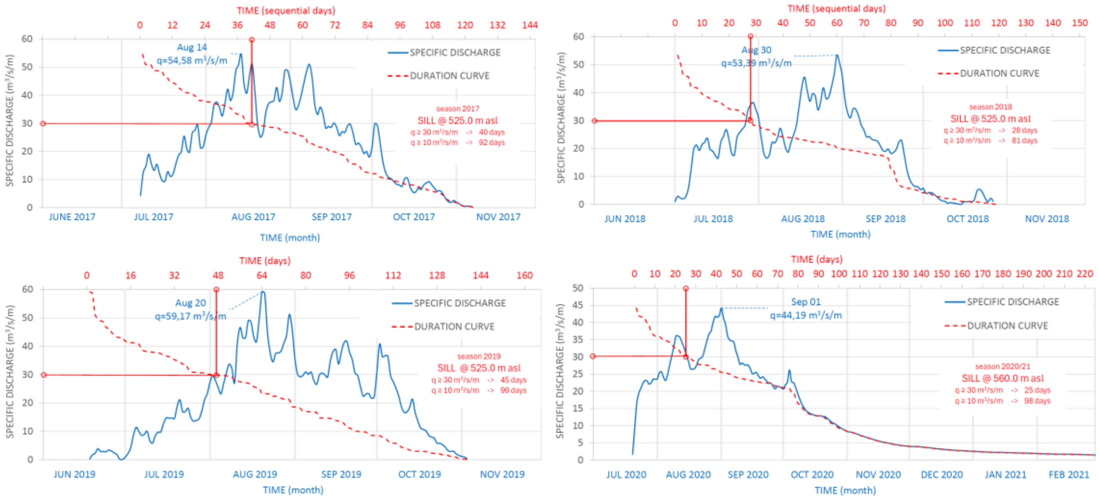


Figure 5 – GERD, Temporary stepped spillway, specific flow discharge, years 2017 – 2020

It is noted that the conventional limit of 30 m^2/s, suggested by many authors for the safe operation of stepped spillway, was exceed during the low block overtopping for more than forty days during 2017 and 2019, for more than twenty-five days during 2018 and 2020, and for six days during 2021.

It is also noted that the potential hydraulic power discharged by the stepped spillway (i.e., without considering the energy dissipation efficiency of the chute) during the day of flood peaks was considerable high, ranging between 6400 MW and 7000 MW in 2020, 2021 and 2022, corresponding to specific values of 24.5 and 27.0 MW/m respectively.

Despite the described heavy operating conditions, no sign of damages and cavitation phenomena were observed during the inspection carried out every year at the end of the rainy season both on the steps along the chute and on the bottom protection slab, confirming the excellent performance of the temporary stepped spillway, both in terms of energy dissipation efficiency and effective aeration.

Figure 6 – GERD, Temporary Stepped Spillway with sill at 560 m asl (September 1st, 2020).

Figure 7 – GERD, Temporary stepped spillway, April 2024 general view after 7 years of heavy operation

3 HYDRAULIC BEHAVIOUR – EVALUATIONS VERSUS PROTOTYPE OBSERVATIONS

The hydraulic behavior of the stepped spillway during the temporary operation was analyzed at design stage by means of both empirical formulae and CFD analysis. As far as the CFD analysis is concerned, a fully 3D model of a 10 m wide strip of the stepped chute was implemented and run to assess its flow characteristics and dissipation performance. The following table reports the considered operating conditions. It is noted that at design stage the sill width was envisaged equal to 275 m. This width was then reduced to 260 m for construction reason.

Table 2. Tested flow conditions

Sill Elevation	Discharge		Tail Water Level
m asl	(m^3/s)	(m^2/s)	m asl
	5 600	20.4	506.5
560	12 000	43.6	511.1
	14 700	53.5	512.4
595	8 650	31.5	509.9

3.1 *Velocity fields*

The following figures provide two examples of the modelled velocity fields in the case of temporary stepped spillway with sill at 560 m asl, and for discharge equal to 12000 and 14700 m^3/s respectively.

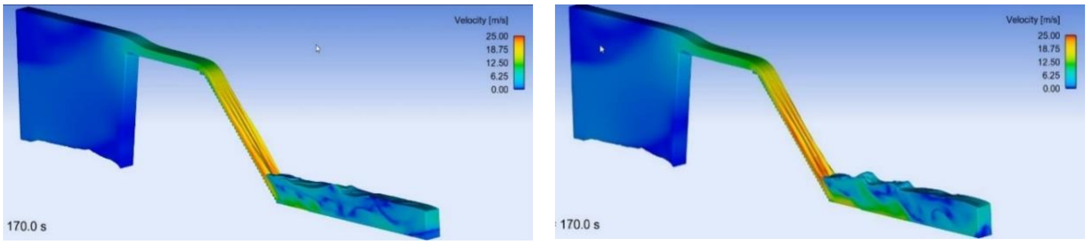


Figure 8. Sill at 560 m asl. Velocity field for Q= 12000 m^3/s (L) and Q= 14700 m^3/s (R)

The values of the estimated depth-integrated flow velocities at the top and bottom of chute are shown in the following table. A tentative evaluation of the velocities observed at prototype scale along the stepped spillway for different flow conditions using Image-Based Measurement Technology is in progress. If successful, the results will be published in the next future.

Table 3. Expected flow velocities along the stepped chute

Sill Elevation	Discharge		Velocity along the chute	
			top	bottom
m asl	(m^3/s)	(m^2/s)	(m/s)	
560	12 000	43.6	11.60	13.50
	14 700	53.5	12.60	16.10
595	8 650	31.5	10.50	17.50

3.2 *Inception point location*

The inception point location were evaluated by both theoretical formulae, and CFD analysis under different operating conditions.

The following figure provides a snapshot of air-entrainment fields in the case of temporary stepped spillway at 560 m asl, and for discharge equal to 12000 m^3/s. It is noted the start of air entrainment at about 15 m from the crest, being the flow downstream invariably well-aerated. The aeration persists all along the stilling basin.

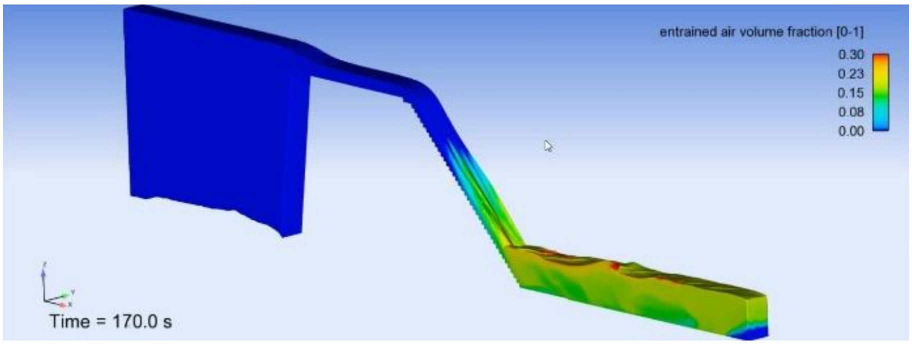


Figure 9 – Sill at 560 m asl. Air-entrainment field for Q= 12000 m^3/s.

The following table provides the comparison between the inception point location evaluated by means of empirical formulae (Boes & Hager, 2003a,b), and that resulting from the CFD analysis. A quite significant difference between the two evaluations is noted. According to the CFD analysis, the aeration of the flow appears to be several meters upstream with respect to that predicted by the empirical formulas. This trend is further confirmed and emphasized by the observations made on the prototype as described hereafter.

Table 4. Inception point location for different flow condition. Theoretical vs. Numerical model results

SILL @ 560	THEORETICAL CLACS		FLOW 3D - MODEL		
Q m^3/s	Inception Elevation m a.s.l.	L along pseudo-bottom m	Inception Elevation m asl	Entrained air %	L along pseudo-bottom m
5600	533	38	555.5	0.6	6
			546.2	2.5	20
12000	510	71	549.7	0.5	15
			542.0	1.1	25
14700	501	83	550.4	0.8	14
			544.6	1.2	22

During the operation of the stepped spillway in 2020 (with sill at elevation 560 m asl) and 2021 (with sill at elevation 575 m asl) the flow along the stepped chute was monitored in order to assess the location of the Inception Point (IP) while simultaneously evaluating the overflow discharge (Q). The evaluation of the IP location was carried out analyzing drone-taken-photos. About 180 measurements were taken with discharged flow ranging between 480 and 11400 m^3/s. The following figure shows an example of how the IP elevation for a discharge of 5100 m^3/s with sill at elevation 575.6 m asl.

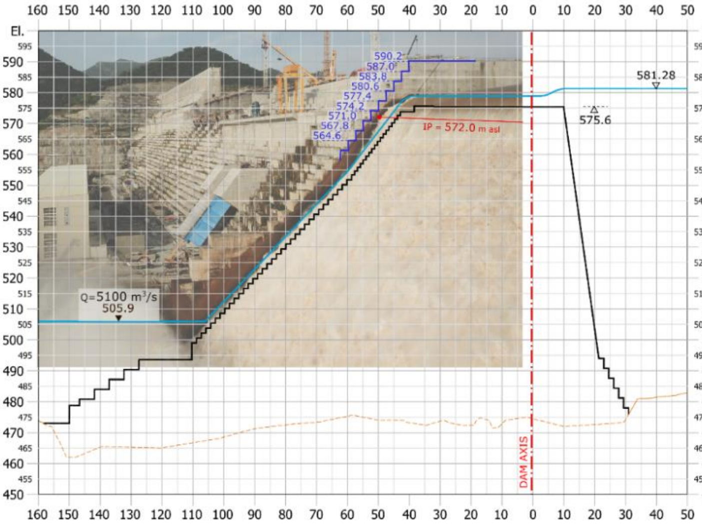


Figure 10. Sill at 575.6 m asl. Q=5’100 m^3/s (19.6 m^2/s).

The observed IP elevations have been then compared with those obtained from the theoretical calculations. The comparison described in the following figure clearly shows that the behavior of the stepped chute on GERD prototype is substantially different from both theoretical/experimental expectation, and CFD results.

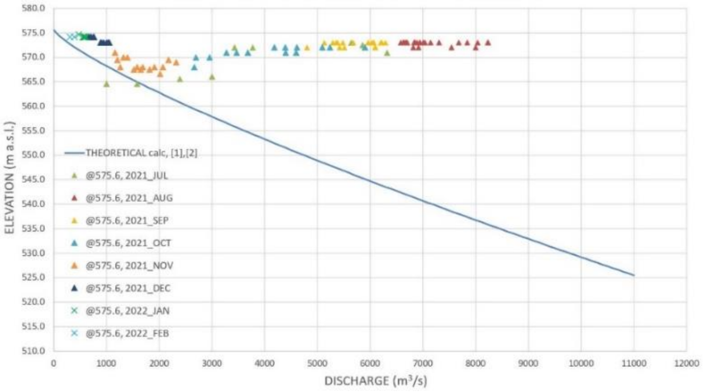


Figure 11: Sill at 575.6 m asl. Inception point. Prototype observation vs theoretical calculations [1],[2]. All discharge values.

In fact, except that for lower discharge values up to about 2000 m^3/s , equivalent to a specific flow q= 7.7 m^2/s, the elevation of the IP is constantly located few meters below the top edge of the chute, whereas according to theoretical calculations at increasing value of discharge the IP should progressively move downstream along the chute and reach an elevation about 50 m below the top of the chute with specific flow q= 40 m^2/s.

This discrepancy between theoretical expectation and prototype measurement is likely due to the shape of the crest. In-fact, the large first step (1.8 m high and 4.5 long), foreseen at the downstream edge of the sill for construction reasons, likely acted as a turbulence promoter, thereby facilitating the air entraining at the beginning of the chute.

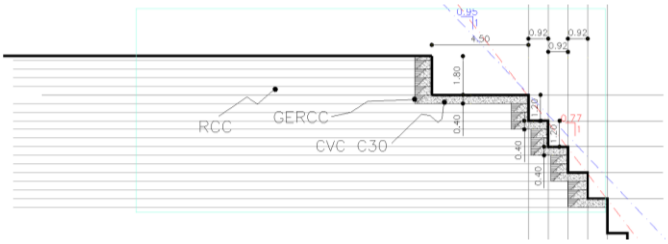


Figure 12: Dimension of first step at the downstream edge of the sill

3.3 *Average dynamic pressure on steps*

Four piezometers were located on the stepped spillway before the 2022 rainy season. Two were located at the middle of both the run and the rise of the step at elevation 542.0 m asl and two at the middle of both the run and the rise of the step at elevation 524.0 m asl. At the time, the crest of the low block was at an elevation of 600.0 m asl, i.e., at a distance (L) along the pseudo-bottom from the crest of 77.2 m and 92.0 m respectively from the piezometers located at the elevation 542.0 and 524.0 m asl. The roughness height of a step measured perpendicular to the flow direction was k_s=1.102 m. The following plots compare the not dimensional average pressures (P/γ/h) actually observed at both run and rise of the step at the elevation 542.0 m asl with the results provided by Sanchez-Juny et al. (2007, 2008) for similar values of the not dimensional parameters L/k_s and y_c/h.

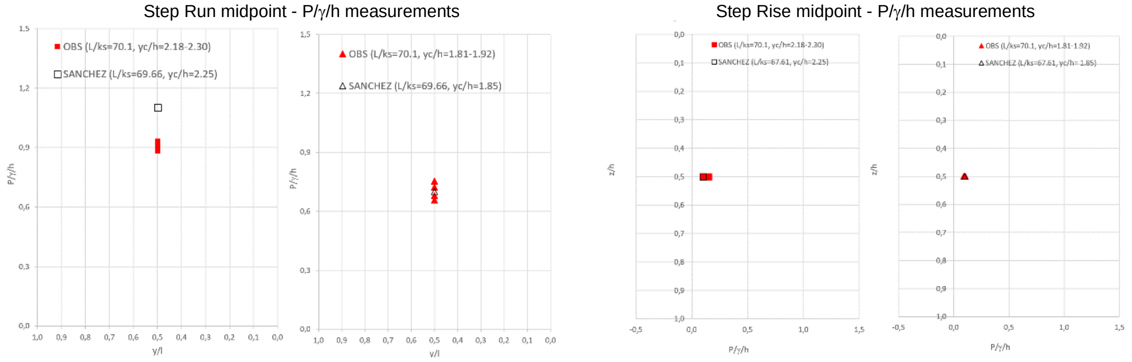


Figure 13: Comparison between observed pressure values on step at elevation 542 m asl and results of laboratory tests by Sanchez-Juny et al. (2007, 2008)

As shown by the plots, the evaluations carried out by Sanchez-Juny et al. (2007, 2008) appear confirmed by the actual prototype observations, at least at both mid-run and mid-rise.

4 BEHAVIOR OF THE DISSIPATING STRUCTUREs

The residual-head at submerged jump entrance for the case of stepped spillway was evaluated both with the theoretical calculations according to Ohtsu et al. (2004) and verified with values resulting from the numerical modelling. The following table shows the theoretical and numerical model resulting residual for the case of crest elevation at 560 m asl.

Table 5– Temporary stepped-spillway with crest at 560 m asl. Residual-head at submerged jump entrance.

Q	Z_{SLAB}	P	V	$H_{AVAILABLE}$	$H_{RESIDUAL}$	$H_{RES,OHTSU}$	$\Delta H_{AVAILABLE}$	$\Delta H_{RESIDUAL}$	$E_{DISSIPATED}$
m^3/s	m asl	Kpa	m/s	m asl	m asl	m asl	m	m	%
5600	497.4	35.7	10	565.7	514.2	516.5	68.1	16.6	75.60
12000	497.4	93.6	13.5	569.3	525.4	523.8	71.7	27.8	61.20
14700	497.4	75.2	16.1	570.5	526.1	525.9	72.9	28.5	60.90

The table shows that the residual head calculated according to Ohtsu et al. (2004) comply with that resulting from the numerical modelling. Furthermore, it is noted that that between 61% up to 75% of the flow energy is dissipated along the stepped chute while the residual amount shall be dissipated in the stilling basin.

According to the numerical model, a submerged jump invariably forms at the stilling basin. The following figure shows the profiles of the velocity components u, v and w at selected locations along the stilling basin for the case of discharge at 12000 m^3/s and sill at 560 m asl.

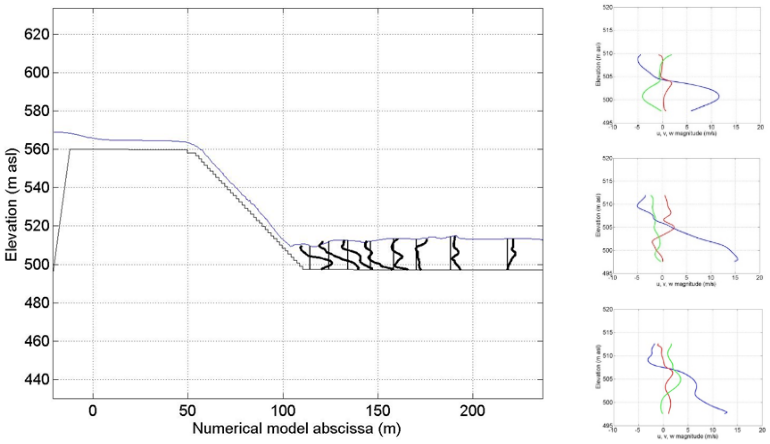


Figure 14. Temporary stepped-spillway with crest at 560 m asl. Profile of the velocity components (u, blue; v, red; w, green) at selected locations along the stilling basin (Q= 12000 m^3/s).

Numerical pressure time series at 20 selected locations along the slab and downstream portion of the modelled domain were extracted and analyzed to get an understanding of the dynamic forcing acting on the overall stilling basin. The analyzed time series span 100 s and are sampled at a frequency equal to 20 Hz (one sample every 0.05 s).

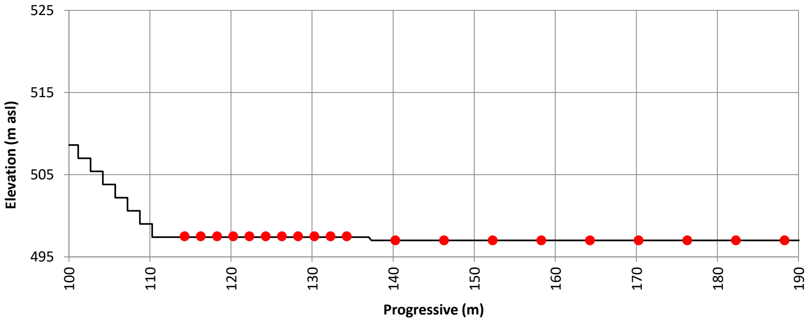


Figure 15. Location of observation of the pressure time-series.

This analysis made it possible to provide an estimate of both the average dynamic pressures and the stream power acting at the stilling basin bottom. The following figure provides an example of the distribution of both the dynamic pressure and the specific stream power at the bottom of the stilling basin along the full length of the hydraulic jump, for a discharge Q= 14700 m^3/s and Sill at elevation 560 m asl.

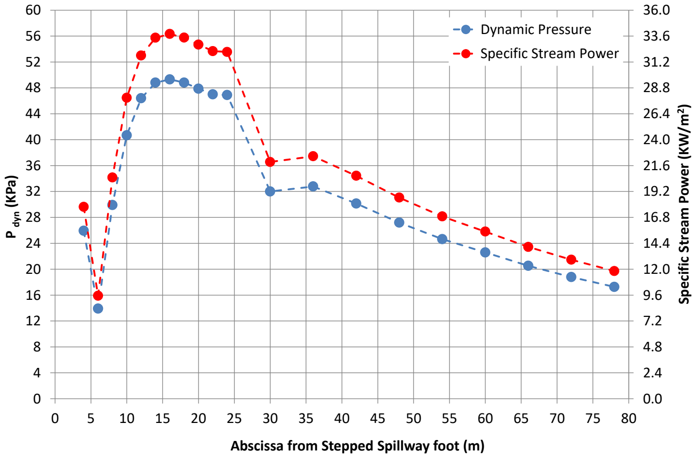


Figure 16. Temporary stepped spillway with crest at 560 m asl. Total dynamic pressure $P_{dyn,k}$ and the specific stream power $W_{b,k}$ acting on the stilling basin bottom (Q= 14700 m^3/s).

It is noted that the main portion of both pressure and stream power appear to be applied on the first 30 m downstream the stepped chute foot. Furthermore, the value of specific stream power (kw/m^2) acting at the bottom appears largely lower than threshold values estimated for both the concrete protection slab and tailrace invert rock mass. Based on the above assumption the length protection slab at the bottom of the stepped spillway chute has been limited to 27 m, equivalent to 35 % of total length of the hydraulic jump.

The 3.8 m thick concrete slab, set at elevation 497.4 m asl was anchored to the foundation with grouted "Dywidag" bars nr.1, phi32 every 2.2 m^2. The downstream portion of the stilling basin and the tailrace channel were excavated with the invert set at 494 m asl in good quality rock mass and minor weaker alignments.

A bathymetric survey was carried out in January 2024, at the downstream dam toe, to verify actual conditions of the stilling basin. A minor scour of about 2-4 meters (minimum 490 m asl with respect to the original excavation level of 494 m asl,) was observed within an area around 100 m long and 60 m wide located downstream protecting slab, while no sign of damage was observed at the slab. Considering the long period (7 years) of temporary operation characterized by large floods and high hydraulic heads, makes it possible to conclude the good dissipating performance of both stepped chute and stilling basin, therefore confirming the design's assumptions and calculations.

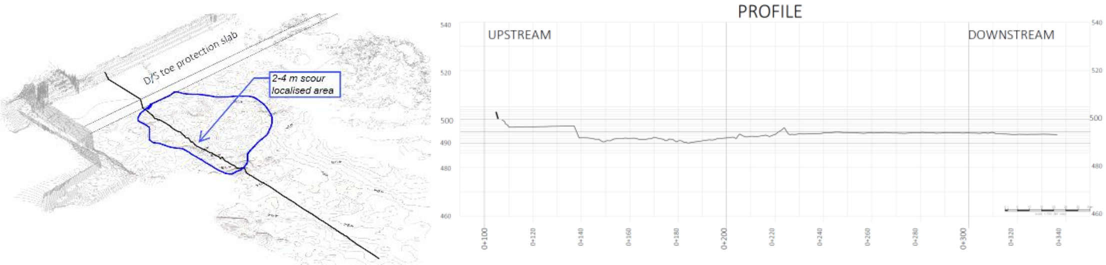


Figure 17. GERD, Plan and profile of the 2024 bathymetric survey at the downstream dam toe

Figure 18. Bottom Slab status after seven years of duty operation

5 CONCLUSIONS

Seven years of heavy operation of the GERD auxiliary stepped spillway made it possible to carry out some comparison between its expected theoretical behavior and the actually observed one.

The huge amount of data collected allowed to evaluate several aspects of the hydraulic behavior of the spillway operating under large discharge conditions even exceeding the specific value of 50 m^2/s.

Among other aspects, the main factors analyzed include: aeration and energy dissipation performance, flow depths and velocities along the chute, stilling basin behavior, sensitivity of step's concrete strength versus of occurrence of damages.

This paper describes some of the most interesting findings gathered from the observations and measurements carried out on the prototype.

It has been noted that the elevation of the inception point was invariably higher than theoretically expected, likely due to the crest shape. Despite exceeding for more than 20 weeks in five years of operation, the conventional limit of 30 m^2/s - suggested by many authors - no cavitation damage was observed, likely due to strong aeration. Only negligible scour was observed in the stilling basin downstream of the protecting slab, and no signs of damage were observed on the slab itself. The observed average dynamic pressures on the steps confirmed the laboratory experimental observations.

Based on the above findings it can be stated that the measurements collected in the field provided better results than those anticipated during the design phase, especially regarding the consistent performance of the spillway even at high discharge rates, the strong aeration, and effective energy dissipation along the stepped chute and in the stilling basin.

These results are very satisfactory and strongly encourage exploring the various topics more deeply to develop effective and realistic design tools, aimed at the technical, operational, and economic optimization of similar projects.

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