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# Koraci u rekonstrukciji za poboljšanje perfrormansi rada zatvarača na temeljnom ispustu

# Reconstruction Steps to Improve Performance of a Dam Bottom Outlet Regulation Gate

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***Rezime -*** Brane i hidroelektrane u regionu Balkana, posebno u zemljama bivše Jugoslavije, dolaze u period kada se moraju razmotriti rekonstrukcijski radovi, da bi se produžio njihov radni period i poboljšao njihov učinak. Sledeći rad predstavlja sublimaciju serije koraka preduzetih za rekonstrukciju i poboljšanje performansi regulacionih tablastih zatvarača na temeljnom ispustu brane. Kako su se nekadašnji standardi malo razlikovali od današnjih, a i proizvodnja opreme je bila drugačija, glavni izazov je bio preduzeti određene korake, kao što su pristup analitičkom proračunu, numeričke CFD i FEA simulacije, kao i mehaničkoj radovi na rekonstrukciji, kako bi se napravio obim radnih tokova na tablastom zatvaraču, poboljšao radni opseg, smanjilo opterećenje podizanja i poboljšale vibracije zatvarača. Sprovedene su numeričke simulacije uslova isticanja kroz temeljni ispust, a kasnije su dokazane snimcima dronom gde se posmatra tok isticanja. Izvršena su i puna suva i mokra merenja pre i posle rekonstrukcijskih radova, gde je postignuto značajno poboljšanje performansi rada zatvarača.

***Ključne reči*** – Zatvarači, Rekonstrukcija, CFD, FEA, Poboljšanje performansi

***Abstract -*** Dams and Hydropower plants in the Balkan region, especially in the countries of Ex-Yugoslavia, are coming to a period were reconstruction works have to be considered, to prolong their operational period and to improve their performance. The following paper represents a sublimate of series of steps taken for reconstruction and performance improvement of a Dam Bottom Outlet Regulation Gate. As the standards back in those days were slightly different from todays, and the equipment manufacture was also different, the main challenge was to take certain steps, such as analytical calculation approach, numerical CFD and FEA simulations and also mechanical reconstruction works, to make scope of workflows on the hydraulic gate, to improve operational range, reduce lifting loads and improve gate vibrations. Numerical simulations of the outflow conditions of the bottom outlet were carried out, and later were proved with drone footage to observe the outflow pattern. Besides, full dry and wet test measurements were made before and after reconstruction works, where significant performance improvement of the gate operation was achieved.

***Index Terms*** - Hydraulic Gates, Reconstruction Works, CFD, FEA, Performance Improvement

## I INTRODUCTION

Reconstruction works on hydraulic gates are not prescribed by any standard and are mainly based on the practical experience of the engineers throughout the years of work with this type of hydromechanical equipment. Mainly, the minimal basis of the reconstruction works is known, where obligatory is the change of seals, wheel axles, bearings or bushings and bolts, and gate body corrosion protection coating application. Except for the mentioned essential mechanical works, the proof is needed that the gate will perform without any obstacles throughout the years, for any load case which can occur on-site.

In this paper, a brief description is given of all reconstruction steps taken to improve the performance of a bottom outlet regulation gate, such as analytical calculations and numerical simulations, 3D CAD modelling, on-site mechanical works and field tests to prove that the reconstruction works improved the overall gate performance. The scope of the work took place in the summer of 2021, on the bottom outlet regulation gate of HPP Rama in Bosnia & Herzegovina. Briefly, the main problem which was settled was that the gate couldn't perform full opening, increased flow leakage was present on-site, intense corrosion was present on several mechanical vital parts and seals and wheels frictional wear have reduced their full functionality. The maximal water height acting on the gate is $H = 95\ [m]$, and the gate has overall dimensions of 4.3x3.3 [m] and weight of app. 24 tons.

## II DAMAGES ASSESSMENT

Pre-reconstruction phase was to inspect the gate as it is and to find out eventual damages on the gate slots and body, if any. The gate was installed back in 1964, app. 57 years old equipment, which was partially functional. The main issue was that the gate was not 100% operational, i.e. it could perform only 50% opening, which endangers the functionality of the dam bottom outlet, disabling evacuation of increased amounts of water and the self-closure (gravitational closure) criteria of the gate was brought to a question.

At first site, several damages were noticed. Primarily, the gate lip and the bottom seals were accessible to inspect eventual damages. A missing part was noticed on the bottom face of the side seal, where local water leakage was allowed. Second, as the discharge rates through the bottom outlet are excessive and the flow velocities are high, the water wears rocks and stones which hit the bottom of the gate and caused local damages on the gate body and the seals (Figure 1).

**Figure 1.** Local damages at the gate bottom (left – gate lip caverns from rock hits, right – side seal bottom face damage)

The following items described are the wheels and the wheel axles. Before reconstruction, damage was noticed on the wheel tracks, as the lower wheels which carry the highest loads were substantially pressed towards the wheel tracks and their initial rolling was blocked. That led to local damage of the wheel tracks, reducing the wheel rolling surface diameter and forcing the gate to slide towards the side bumpers, leading to increased friction and damages on the side sliding tracks (Figure 2).

**Figure 2**. Wheel track damage (left) and side bumper contact with the sliding track (right)

When the site was ready to perform gate dismantling, an interesting phenomenon was noticed – the gates center of gravity with the pre-described holes for the hydraulic cylinder and the hinges were miss-matched. The gate weight is app. 24 tons and when pulling out, the gate got stuck on the side bumpers and the side tracks. This situation was outrun by cutting out the side bumpers to release the gate and pulled out into the revision space (Figure 3). Later, new side bumpers were installed within the tolerances.

As the gate was pressed towards the side bumpers, the wheels were not performing contact with the wheel tracks, which is unacceptable (Figure 4). Also on Figure 4 it can be noticed the surface damages on the wheel rolling surface which results in reducing the rolling diameter of the wheel, which increases the pressure on the seals. These damages were initially noticed and represent some of the main disadvantages of the gate which lead to increased lifting resistant forces of the gate, and negatively contribute towards performance of full lift, which was the main issue.

**Figure 3.** Side bumpers cut-out to release the stuck gate

**Figure 4.** Wheel not in contact with wheel track

## III Mechanical Works and Design Calculations

After dismantling all mechanical elements, sand blasting was applied on the gate body and the gate slots, to clean the surfaces and to make them rough to better accept the anticorrosive coating. Corrosion damages were noticed especially at the sections where the wheel axles covers were attached. On Figure 5 a comparison is shown before and after the sand blasting.

**Figure 5.** Before (Left) and after (Right) sand blasting

As the standards and practices back in the days were different than today's methods, the challenge was primarily to re-design certain mechanical elements, such as bearings, wheel axles and their sealings, as standard equipment sizes have changed over time.

Primarily, the seals' dimensions for the gate were made by JUS standards which needed to be specially molded from Nitrile Rubber with 50 Shore rubber hardness, to perform „soft“ contact with the sealing frame and to be pre-compressed within the allowable limits. The seal plates and bolts were completely replaced, made from stainless steel. The sealing frame in the lower gate slot was also made from stainless steel, where the damaged sections were refurbished by welding stainless steel on them, and then adjusting at the right thickness. As the gate lifts and gets in the upper slot, the seals are always in contact, and the gate performs sealing throughout the operating height. The material of the gate slot is structural steel and the seals must remain in contact all the way.

The seals profiles are given on Figure 6 by JUS standards. Today's seals by European standards cannot fit in the pre-described sealing space. The seals between each other were glued to obtain a sealing unity. On Figure 7 the top seal is presented after refurbishment with the sealing plates and new bolts from stainless steel.

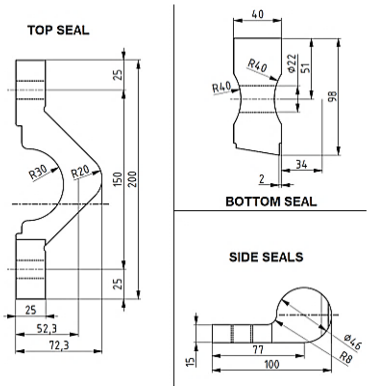


**Figure 6**. Gate seals profile dimensions by JUS standards

**Figure 7**. Gate top seal after refurbishment

The wheels where refurbished and their axles were re-designed. The purpose of the re-design of the axels was to reduce the contact pressure inside the rolling surface and to reduce rolling friction, which will reduce the lifting forces and allow the gate to perform full opening. Primarily, the wheel was sent to a workshop for cleaning, machining and the rolling surface was welded with stainless steel. The wheel axle hole diameter was decreased for 7 [mm] from Ø347 to Ø340 to put a pair of roller bearings packs with outer diameter of Ø340 and inner diameter of Ø220, compared to the old axle with outer diameter of Ø210. Also, the axle was bored with channels to allow lubrication of the roller bearings, where the old axle had self-lubricating copper bushings.

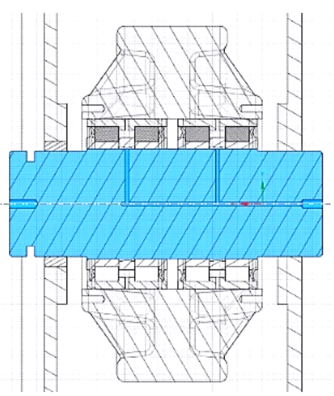

**Figure 8**. Wheel axle redesign

**Figure 9**. Refurbished wheel with welded stainless steel and packed with roller bearings

To perform this type of design, FEA simulations were carried to analyze the stress and strain behavior of the wheel assembly. The new design led to reducing the material grade quality from 1.4057 (original axle material) to 1.4301, obtaining a safety factor of the wheel of 1.355 (Figure 10).

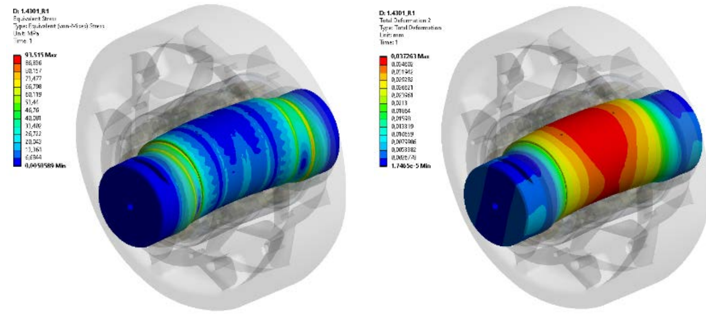

**Figure 10.** FEA analysis of the redesigned wheel assembly

Other mechanical FEA simulations were performed on the gate body, according to real measured material thicknesses, to obtain the stress and displacement behavior of the gate body and its critical sections, and also the determine the natural frequency of the gate, as later vibration measurements were performed to see how the reconstruction has overall influence on the gate improvement.

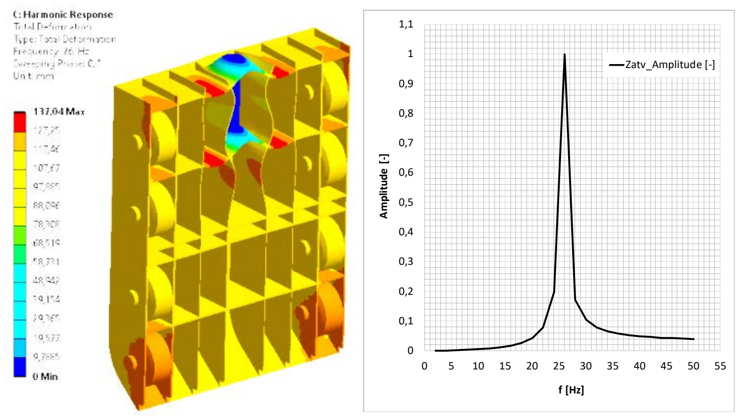


**Figure 11.** Harmonic response of the gate and its natural frequency at 26 [Hz]

## IV CFD Estimation of Hydrodynamic Forces

As the primary criterion is to obtain self-closure of the gate, hydrodynamic forces estimation via CFD simulations is inevitable in the process. Using the Multiphase Flow Modelling approach with the Volume of Fluid (VOF) method, the gate was numerically tested from closed to opened position at different water levels in the reservoir. A 3D model was built, considering short segment of the bottom outlet and the outflow conditions in the atmosphere, considering a simplified terrain configuration behind the gate. The results of the CFD simulations show remarkable correspondence with the Model Tests of the bottom outlet performed 50 years ago.

The obtained results for the hydrodynamic forces showed that at every gate position, the forces are positive downwards which creates the Down-pull effect of the gate, leading towards self-closure of the gate (Figure 13). The water jet formation behind the gate from the CFD simulations was compared with drone footage, where at the same positions, the outflow conditions were filmed, showing similarity with the real operating conditions (Figure 14 and 15).

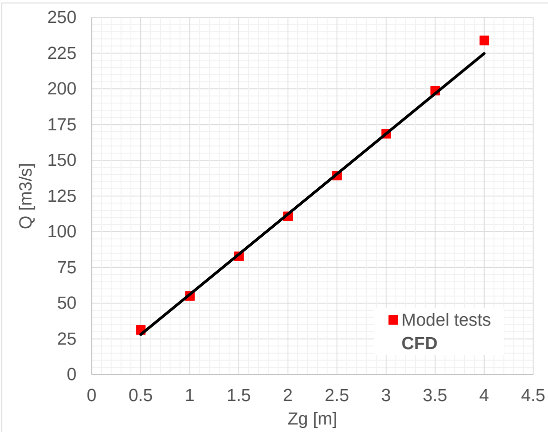


**Figure 12.** CFD obtained discharge rate compared with model tests data

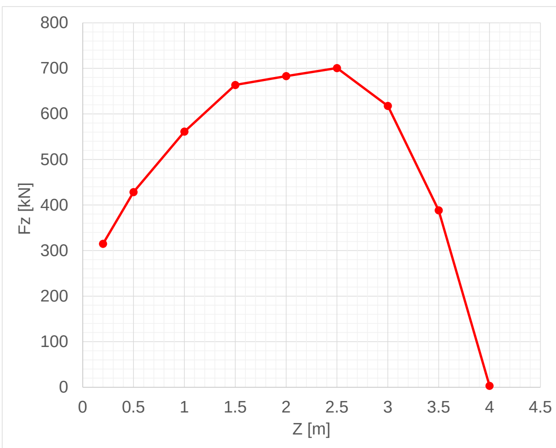


**Figure 13.** CFD obtained vertical hydrodynamic force on the gate

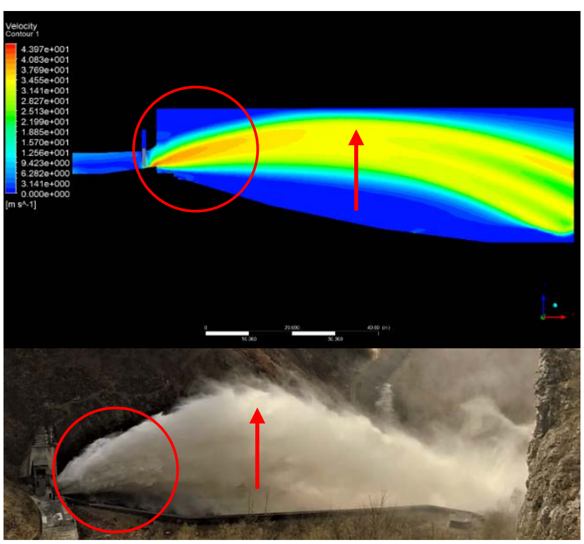

**Figure 14.** Gate opening at 5 [%]

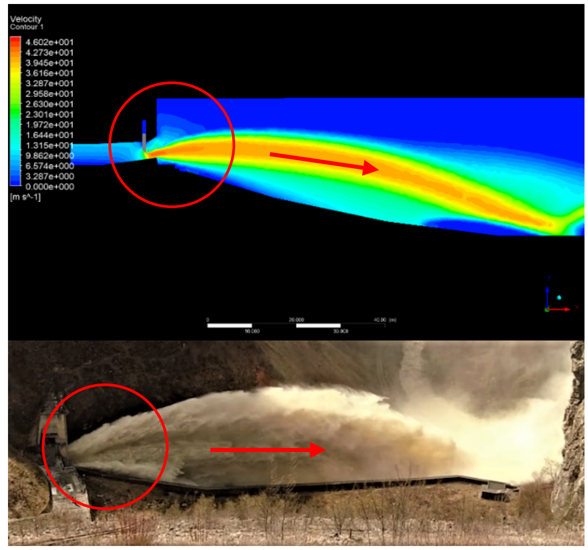

**Figure 15.** Gate opening at 37.5 [%]

The jet formations behind the gate obtained with CFD simulations show good correspondence with the drone footage of the outflow conditions, where for smaller gate openings the jet is more humped and shortened, and for increased opening, is flattens and has increased length. Discharge rates depends from the water level in the reservoir, and it was obtained for maximal water level in the reservoir of app. Q=250 [$m^3$/s] for full gate opening.

## V Gate Tests and Measurements

Pre-reconstruction and after-reconstruction tests and measurements were carried out to see the differences in the performance, i.e. the vibrations and the lifting pressures. The tests are dry tests without water pressure and wet tests.

Dry tests were carried out to see the mechanical behavior of the gate of its own. The measured results showed no change in the natural frequency of the gate after the reconstruction. The measured natural frequency was obtained as 26.875 [Hz], showing that the harmonic response simulations from the previous chapter (26 [Hz]) show good correspondence with the measured values. Also, it was obtained that the lifting pressure was reduced by 19 [bar] after the reconstruction (Figure 17).

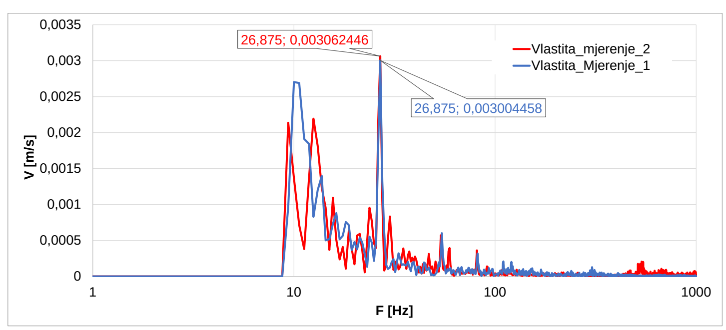


**Figure 16.** Gate natural frequencies comaprison

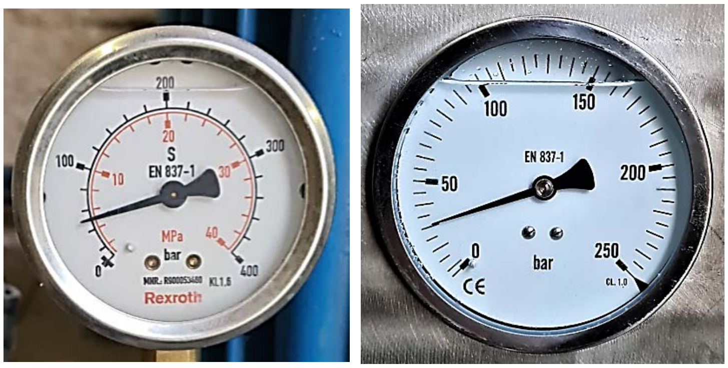


**Figure 17.** Dry lifting pressure comparison
(left 50 [bar] – pre; right 31 [bar] – after reconstruction)

The wet tests showed that for partial openings of the gate below 20% where they represent the most critical opening positions, a significant reduce of the vibrations was achieved.

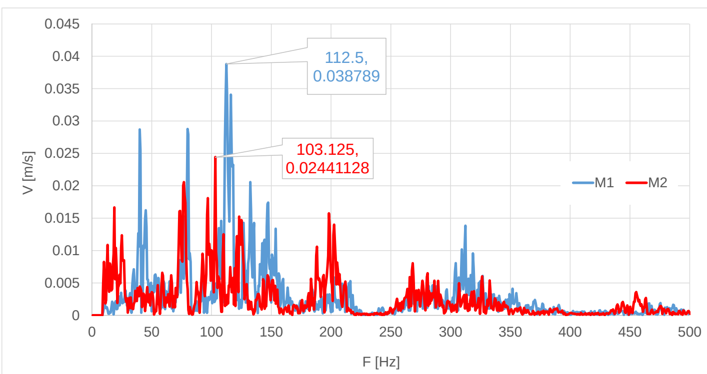


**Figure 18.** Vibration comparison for 6.25% opening

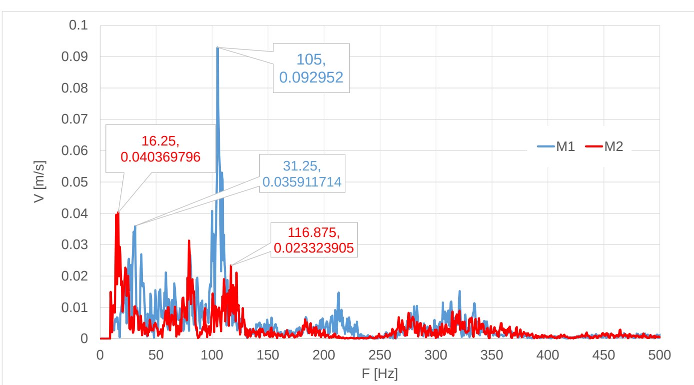


**Figure 19.** Vibration comparison for 12.5% opening

From figure 18, it can be seen that vibrations velocity after the reconstruction works was reduced by 37% and the vibration frequency for 8.3% for gate opening of 6.25%, and on figure 19, for gate opening at 12.5%, the vibration velocity was reduced by 67% and the frequency for 28.5%. Due the lifting, the pressure was measured needed to lift the gate. A reduce in the lift was obtained from 22 to 48% throughout the gate path.

All of the measurements done showed decreased values of the gate loads, whether they were vibrations or lifting loads. This shows that all the steps taken to refurbish the gate contributed towards improved gate performance. To validate the numerical simulations and analytical calculations with the measured data, mathematical models for the seals friction and wheels rolling friction were derived and were coupled with the CFD calculations of the hydrodynamic forces, to obtain the lifting pressure in the hydraulic cylinder.

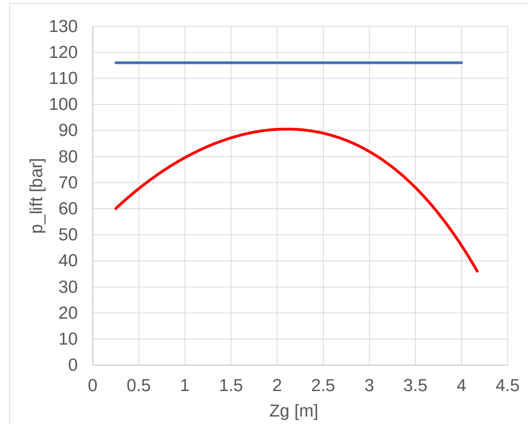


**Figure 20.** Lifting pressure comparison pre and after reconstruction

According to [1], as the wheels were packed with sets of roller bearings, the rolling friction of the wheel and the bearings were adopted as:

$$\mu_1 = 0.2\ [-] \tag{1}$$

for the wheel rolling friction, and

$$\mu_2 = 0.003\ [-] \tag{2}$$

for the roller bearings friction. The total wheel resistance is calculated as [2]:

$$F_{\mu w} = n_w \cdot \frac{2F_{wn}}{D_2}\left(\mu_1 + \mu_2 \frac{D_1}{2}\right) \tag{3}$$

where $n_w$ is the number of wheels on the gate, $D_2$ and $D_1$ are the outer and inner wheel diameters respectively, and $F_{wn}$ is the normal force in one wheel obtained as function of the horizontal hydrostatic force $F_x$ obtained from the CFD simulations acting on the gate as the gate lifts:

$$F_{wn} = f(F_x)\ ;\ F_x = f(Z_g) \tag{4}$$

The seals frictions were also calculated according to [2] where the friction force also reduces as the gate lifts, as the pressure on the seals decreases:

$$F_{\mu s} = f(p_s)\ ;\ p_s = f(Z_g) \tag{5}$$

The mathematical models were coupled with the CFD results to obtain the needed lifting force, i.e. lifting pressure of the hydraulic cylinder, as:

$$F_{lift} = G_z + F_{\mu w} + F_{\mu s} + F_{DP} \tag{6}$$

where $G_z$ is the gate weight and $F_{DP}$ are the CFD obtained down-pull (vertical) forces on the gate. This model showed good correspondence with the measured values of the lifting pressure of the gate (figure 21), showing that the CFD modelling coupled with the analytical methods are good predictive method for estimating real loads and operating conditions. To validate the CFD model from another point of view, the static pressure on the gate slot cover were extracted from the simulations and compared with on-site measured pressure values (figure 22).

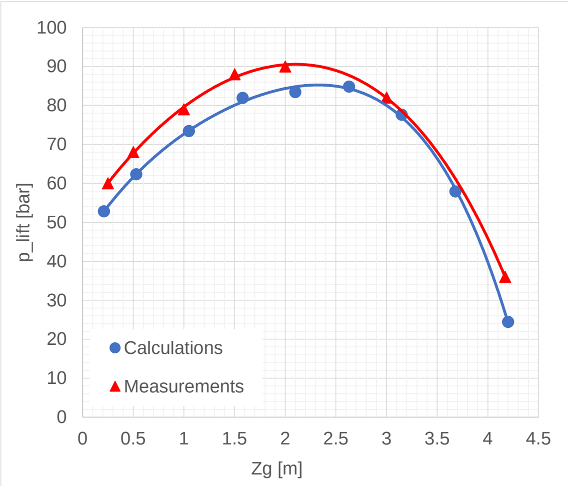


**Figure 21.** Lifting pressure comparison (CFD calculations + analytical models v.s. measured)

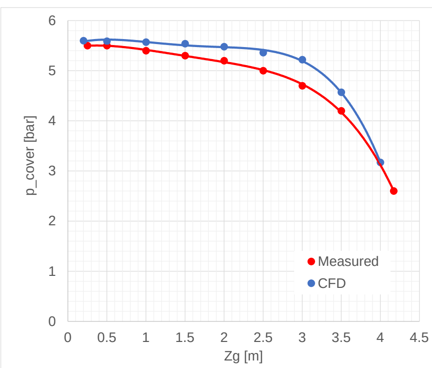


**Figure 22.** Pressure on the slot cover (CFD calculations v.s. measured)

**Figure 23.** Cover pressure measurement

## VIII Conclusions

This paper shows brief explanation of engineering approach steps towards estimating gate operating loads and hydrodynamic conditions, investigating damages on the gate which prevented the gate to fully operate, mechanical works on the gate and measurements to prove all the steps taken that lead to gate operational improvements. The series of works took place in the summer of 2021 on the bottom outlet regulation gate of HPP Rama in B&H.

As the gate was made app. 57 years ago, redesigning of several mechanical parts was needed to improve functionality. The wheels of the gate were refurbished and the wheel axles were redesigned to fulfill the needed mechanical operating conditions, such as reducing friction, which led to reducing lifting pressure and allowance to lift gate to maximum opening, which was not possible before the reconstruction.

Numerical simulations were carried out for the mechanical system (Static Structural) and CFD for obtaining the hydrodynamic conditions, discharge rates and forces which act on the gate. All together were coupled with analytical mathematical models to estimate the lifting loads needed of the gate, where great reducing of the pressure values was obtained, and later was measured on-site.

Vibration measurements were also carried out to compare the benefits from the reconstruction works. The mechanical works haven't changed the natural frequency of the gate, and in partial opening critical positions below 20% opening of the gate, reduction in the vibrations was noticed.

As it was mentioned, fixed reconstruction steps are not strictly specified in the standards and are mainly based on engineering experience. This paper sublimes a successful work done and points out several measures taken to overcome lifting issues of old gates, how to refurbish certain mechanical parts, redesign wheels and axles and predict operating conditions in pre-reconstruction phase, to achieve operational improvement on-site, and to prolong their operating lifetime.

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