Measurement of Moments of Forces on the Control Mechanism of Gate Valves of Hydraulic Power Station

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Abstract: The article discusses the torque measurements on gate valves in the water dam of hydraulic power station. The gate valves serve for regulation of water flow between the pressure chamber and other operational spaces in dam. To open and close the gates, a system of bars (spindles, tubes) connected by universal joints (cardan joints) is employed, guided by a longitudinal guide. Approximately ten years ago, the equipment underwent reconstruction, replacing manual operation with hydraulic actuation for gate manipulation. However, issues arose with opening and closing the gates once the hydraulic actuator and control system were implemented. Furthermore, water entered the hydraulic system. Consequently, manual manipulation became necessary for the gate valves. The article presents an analysis of the causes behind the equipment malfunction. The authors conducted operational measurements of the driving torques of the closing mechanism using their designed dynamometers. These measurements revealed the reason of gate valves malfunction. The analysis of the collected operational data concluded that employing driving units with higher torque is essential for safe and reliable operation. From a strength point of view, the mechanical parts of the linkage are properly designed.

Keywords: Gate valves; Torques; Operational measurement

1 Introduction

Dam structures or water reservoirs are the essential infrastructure of society, used primarily for hydropower, flood control, and irrigation. A decade ago, the number of reservoirs larger than 0.01 ha was estimated to be approximately 16.7 million worldwide, and the number was increasing significantly every year [1]. Information provided in the World Register of Dams database [2], updated in April 2020, considers 58,713 dams classified as large, i.e., dams with a height of at least 15 m measured from the lowest base to the crest, or smaller dams (of height between 5 m and 15 m) that hold more than 3 million cubic meters of water [2]. Using the latest publication of the World Register of Dams, irrigation is the most common purpose of dams. Of single-purpose dams, 48% serve for irrigation, 17% provide electricity generation, 13% ensure water supply, 10% are used for flood control, 5% for recreation, and less than 1% for navigation and fish farming. At present, the number of mainly multi-purpose dams is increasing [3, 4].

The dam described in the article was built between 1963 and 1972. Its purpose is to provide water for the domestic metallurgical industry, electricity supply, flood protection, and recreational purposes. The reservoir has a storage capacity of 45.3 million cubic meters and a flooded area of approximately 4.5 square kilometres. The length of the dam is 11 kilometres. The reservoir also includes a pumped storage hydroelectric power plant with reversible turbines, completed in 1973. It consists of two parts, the second of which functionally forms a balancing reservoir to the pumped storage power station. In 2011, the dam was renovated, with the gates being manipulated to hydraulic actuation. Since the hydraulic actuator and controls were implemented, there have been problems with opening

and closing the gates. This manipulation has subsequently had to be done manually. In addition, during operation, the chamber in which the hydraulic equipment is located was flooded for short time. The operator's preliminary information on the condition of the equipment already indicated that the driving torques of the hydraulic mechanism were insufficient for handling the gate valve. The methodology proposed by the authors for the operational measurement of the driving torques of the closing mechanism not only confirmed the above factual situation but also provided important information leading to the identification of possible causes of the limited functionality.

2 Methods

As mentioned in the introduction, after several months of operation, problems with manipulating the gate valves using servomotors with a tripping torque of 160-400 Nm and a breakaway torque of 500 Nm were already detected. According to preliminary information from the operator, the torque value of 500 Nm was insufficient to operate the gate valves. Two dynamometers were designed and manufactured to determine the torque at the gate valves operating load and thus to find out the possible cause of problem. Their design was based on data provided by the operator. However, this procedure also required strength control of the other mechanical parts of the opening mechanism, such as the tubes and connecting elements (pivots/pins). The tube material's chemical composition and mechanical properties were determined to establish the actual status. After evaluating the material's mechanical properties, operational measurements were carried out to determine the torque required for manipulating the gate valves.

A prototype dynamometer was designed for torque determination, which allowed us to obtain the torque value considering actual operating conditions such as friction, corrosion, shape, and wear of mechanical parts. The essential part of the designed dynamometer was a seamless steel tube of the annular cross-section with an outer diameter of ø50 mm and wall thickness of 5 mm mounted in radial bearings pressed in steel discs. The tube material is S235JRH, with a yield strength of 235 MPa and a strength of 360-510 MPa [5, 6]. When designing the dynamometer dimensions, it was necessary to consider the winding cable length of 25 m for strain gauging. Fig. 1 shows a 3D model of the designed dynamometer.

Since the designed dynamometer served to identify the actual value of the torque required for opening and closing the gate valves, it was necessary to verify not only its functionality but also to perform its calibration in laboratory conditions before the operational measurement. For the calibration measurement, two different measuring apparatuses were used. The values were directly read from the display for the measurement with the P3 strain indicator and recorder (Vishay, USA). The Ouantum MX840 strain gauge apparatus (HBM, Germany) was used with the CatmanEasy measurement and evaluation software. Based on the calibration measurements performed, it was found that a torque value of 400 Nm corresponds to a strain of 319-320 με for dynamometer 1 and a strain of 322-323 με for dynamometer 2. The calibration measurements confirmed a very good agreement so that their possible substitution in the operational measurement would not cause significant deviations (i.e., the deviation of the measurement results would be less than 1%). The measuring chain consisted of a Quantum MX840 strain gauge apparatus and the CatmanEasy evaluation software. In some cases, it was also necessary to use an extender attached to the wheel when the valve gate mechanism was first opened (to apply higher torque).

Fig. 1 Model of the designed dynamometer.

As can be seen from the diagram in Fig. 2, six gate valves (three on the right and three on the left side) are used to fill and discharge water into and out of the pressure chamber, and gate valve 4 is used to discharge water from the pressure chamber into the pump chamber. The operational measurement procedure has been chosen so that the operational modes considered correspond to the worst-case loading mode in a critical situation.

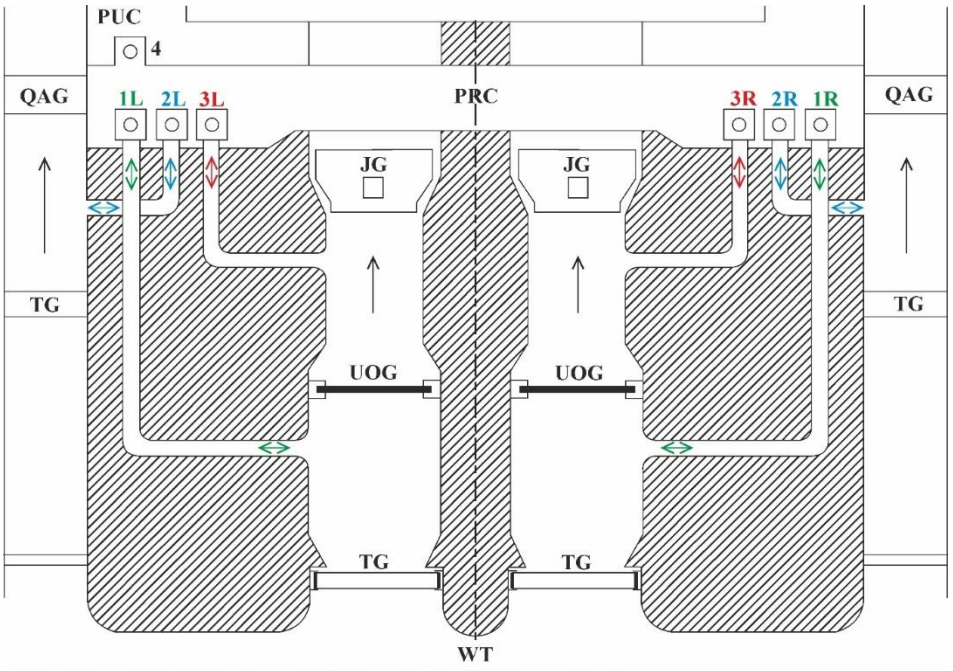


Fig. 2 View of the location of the gate valves under consideration.

For this reason, only the following modes were performed out of all possible modes:

Mode 1: 1L and 1R gate valve handling operation:

- Filling of water from the tank (T) into the pressure chamber (PRC).

Mode 2: 2L and 2R gate valve handling operation:

- Discharge of water from the pressure chamber (PRC) into the zone between the power plant quick-acting gate (QAG) and the temporary gate (TG).

Mode 3: 3L and 3R gate valve handling operation:

- Discharge of water from the zone between the Johnson gate (JG) and the upstream operational gate (UOG) into the pressure chamber (PRC).

Mode 4: gate valve no. 4 handling operation:

- Transfer of water from the pressure chamber (PRC) to the pump chamber (PUC).

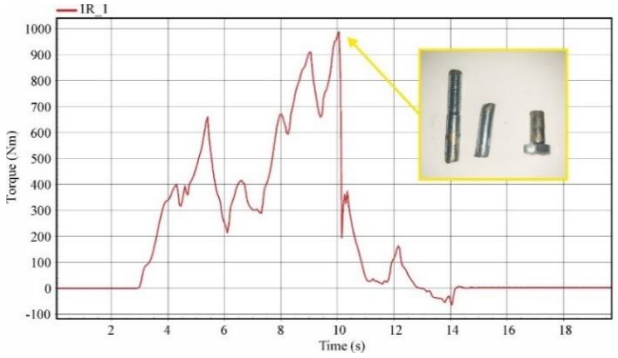
In addition to the above modes, others are used in real operation, but in each of the modes tested, the most unfavourable handling case was when the water column pressure was applied from only one side of the gate valve. Each pair of caps 1L/1R, 2L/2R, and 3L/3R has a different function, so each mode was implemented separately.

Before each measurement, the dynamometers were sequentially attached to individual flanges and their corresponding connecting bars, through which the gates were manually manipulated using a wheel located at the top of the dynamometer. The operator found that 60 turns of the wheel are required to open the gate valve fully. As the opening of the gate valves was manual and in some of the modes tested, the pressure chamber was filled (opening of the gate valve at the bottom of the water reservoir directly below the measuring station), it was necessary to pay special attention to ensure the safety of the operating staff during the operational measurements. Therefore, to increase safety, it was agreed after mutual consultation with the operator in charge that the operational measurements would be carried out at 15 turns of the wheel. This number of turns is related to the fact that the most significant resistance to movement occurs when moving from a stationary position, i.e., when static friction is overcome. During subsequent handling, the increase in the torque value required to operate the gate was no longer anticipated. Another of the proposed safety features for the operational measurement was the replacement of the original 10 mm diameter steel pin with an M8 bolt of material grade 8.8. The ultimate strength of the bolt material used is 800 MPa, and the yield strength is 640 MPa.

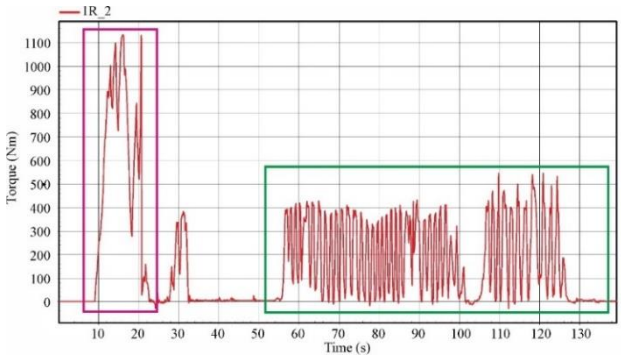
At the assumed maximum torque value (500 Nm), the shear stress in the used M8 bolt is approximately 250 MPa, which according to Guest's strength theory, is strength-compliant. As it later turned out, strain values corresponding to higher torque values were registered in almost every operational measurement. This phenomenon was confirmed by the deformation of the M8 bolts used. In some cases, these bolts failed by shear on the 1R and 2R gates. In standard operation with 1R and 2R gates, the operator uses a 10 mm diameter pin. As no mechanical (steel) parts have failed, the authors used an M10 bolt of material grade 10.9 for further measurements. This bolt has an ultimate strength of 1000 MPa and a yield strength of 900 MPa.

Fig. 3 to Fig. 9 show documented time-dependent records of the torques determined by recalculation from the measured strains based on the calibration measurements. As can be seen from Figs. 3 to 5, much higher levels of torques, which exceeded 1000 Nm in two cases, were determined on the right side of the water reservoir. After consultation with the operator, it was determined that no critical situation requiring simultaneous manipulation of the pair of corresponding gate valves (on the right and left sides) had occurred during the previous

operation history. In regular operation, service personnel use left-hand gate valves. This fact was confirmed by the actual handling during the operational measurements, as documented by the time-dependent torque records in Figs. 6 to 9. Gate valve 4 was the most commonly used, as confirmed by the lowest torque levels, which did not exceed 255 Nm. In Figs. 3 to 9, the areas where it was necessary to release the gate mechanism are marked in red. The green area corresponds to the opening of the gate valve (approximately 15 turns). The closing process is indicated in blue. The purple arrow identifies the instant the gate valve has been fully closed. The yellow arrow identifies the moment the maximum torque value has been reached. When using the M8 bolt, the bolt failed by shear at that instant. When using the M10 bolt, the required release of the locking mechanism was achieved.

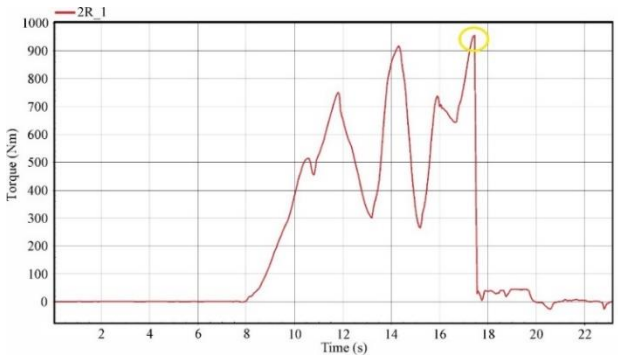


a)



b)

Fig. 3. Time record of torque during manipulation of the 1R gate valve mechanism: (a) failure of the M8 bolt; (b) opening of the gate valve using the M10 bolt.



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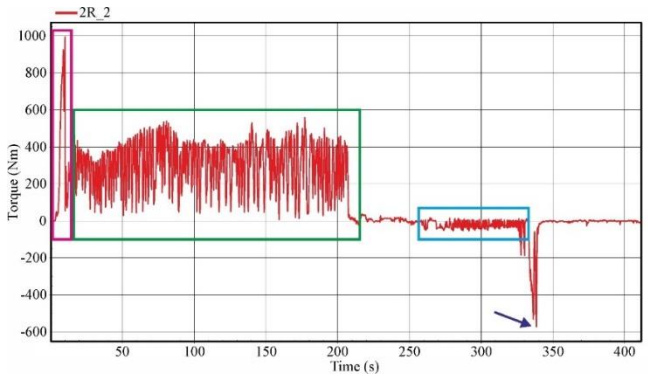

b)

Fig. 4. Time record of torque during manipulation of the 2R gate valve mechanism: (a) failure of the M8 bolt; (b) opening of the gate valve using the M10 bolt.

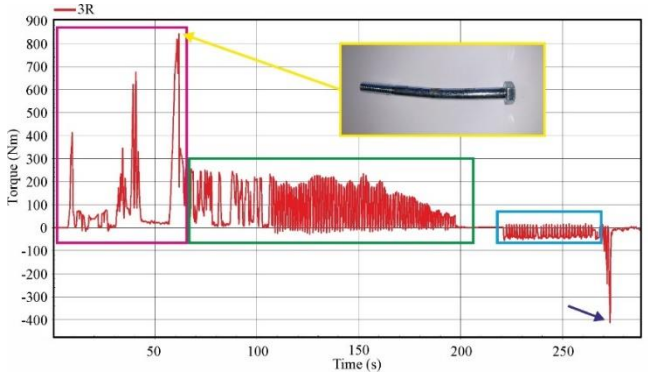

Fig. 5. Time record of torque during manipulation of the 3R gate valve mechanism.

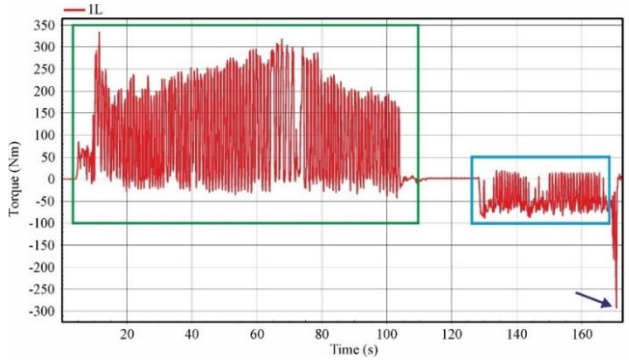

Fig. 6. Time record of torque during manipulation of the 1L gate valve mechanism.

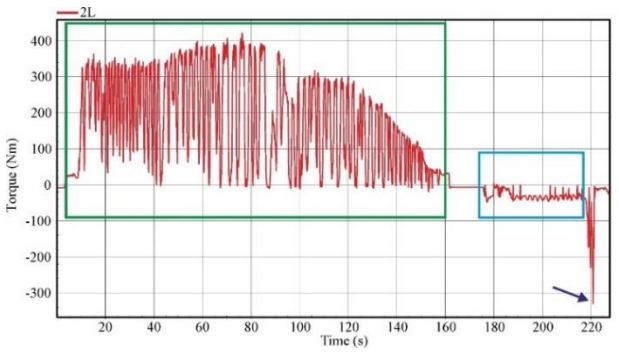

Fig. 7. Time record of torque during manipulation of the 2L gate valve mechanism.

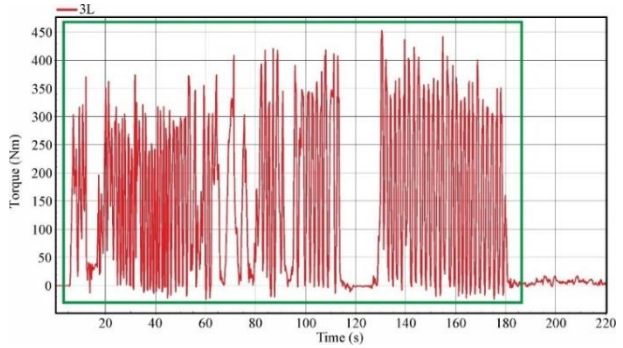

Fig. 8. Time record of torque during manipulation of the 3L gate valve mechanism.

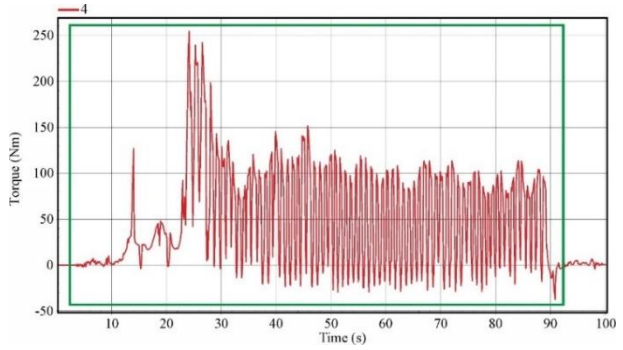

Fig. 9. Time record of torque during manipulation of the 4 gate valve mechanism.

Table 1 shows the maximum values of the torques obtained when opening or closing the closures under consideration. The torques confirm the influence of the manipulation of the gate, as seen by gate 4, which is the most frequently (regularly) used one.

Table 1. Maximum torque values observed when handling gate valves.

Mode	**Obtained value of maximum torque (Nm)**						
	1L	**2L**	**3L**	**1R**	**2R**	**3R**	**4**
Opening	334	420	450	1135*	995*	840	255

**M10 bolt of material grade 10.9 was used*

Discussion and conclusion

Based on the operational measurements carried out, the analysis of the material used, and the subsequent analysis, the following facts can be stated:

- The torque value of the hydraulic actuators of 400 Nm is insufficient for opening or closing the gate valves.
- The maximum torque value obtained during the operation was 1135 Nm. It is the peak value registered in the initial (release) phase of the gate opening when it was necessary to overcome mainly the resistances in the corroded universal joints. The torques were much lower in the subsequent phases after the mechanism started.
- The bar (tube) is made of stainless high-alloy Cr-Ni low carbon steel of likely grade W. Nr. 1.4306 (AISI 304L) with strength characteristics Rp0.2 = 299 MPa, Rm = 607 MPa. When loaded with a torque of 1135 Nm, shear stress is formed in the bar, which exceeds the value of the allowable shear stress but is significantly below the ultimate strength. Thus, the bar is loaded in the elastoplastic region at this stress. When loaded with a torque of 1000 Nm, shear stress is formed in the bar, slightly below the allowable shear stress. This load can be considered limiting when it only occurs in the first stages of the gate valve handling process.
- A visual inspection indicated that the universal joints were significantly corroded, which greatly increases the resistance to movement and requires high driving torques. It should be noted that for vertical manipulation of the gate valve, it is mainly necessary to overcome the friction forces in the mechanism. The experimental measurements' results confirm that the highest torque was only required when the gate valve was opened. Subsequently, the torque values decreased to more than half. From this point of view, paying due attention to the condition of the universal joints and regularly moving them as part of scheduled repairs or maintenance is crucial. Regular opening and closing of the gate valves during maintenance should be carried out in a mode where the gates are not loaded with water so that torque peaks do not occur in the initial stages. It will lead to a reduction in the initial resistance to movement and a reduction in the load on the individual structural elements in the motion chain of the gate valve.

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