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Research paper

Dynamic monitoring as a part of structural health monitoring of dams

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Abstract: Safety of dams and other hydraulic structures is a complex procedure that must consider the individual characteristics of each structure and provide an insight in the structural health at every stage of the structure's life cycle. Failures of structures permanently or temporarily retaining water may cause large economic damage, environmental disasters, and loss of lives. An engineering design should, therefore, guarantee maximum security of such structures or maximize their reliability not only in ordinary operating conditions but also under extreme hydrological load. By performing structural heath monitoring (SHM), the safety can be optimized, including the performance and life expectancy of a structure by adopting an appropriate methodology to observe the identified failure modes for a selected dam type. To adopt SHM to hydraulic structures it is important to broaden the knowledge and understanding of the ageing processes on hydraulic structures, which can be achieved by laboratory testing and application and development of novel monitoring techniques, e.g., vibration monitoring. In Slovenia, we are increasingly faced with the problem of ageing of dam structures. At the same time, we are also faced with changes in the environment, especially with the variability in time-dependent loads and with new patterns of operation on dams used for hydropower, with several starts and stops of turbines happening on a daily basis. These changes can lead to a decrease in structural and operational safety of dams. In this paper we propose a methodology where the dynamic response of concrete dams is continuously monitored in few locations on the dam using accelerometers, while all significant structural members are measured in discrete time intervals using portable vibrometers. We focused on run-of-the-river dams, which are a common dam type in Slovenia. The pilot case for the system is lower Sava River with a cascade of 5 dams used for hydropower.

Keywords: dam safety, structural health monitoring, vibration

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1. Introduction

The main challenge the dam community is faced with ageing of dams, built in times of different safety standards and economical regime, while many of them are already extending their designed exploitation period. For example, in Slovenia, we are increasingly faced with the problem of ageing of dam structures. At the same time, we are also faced with changes in the environment, especially with the variability in time-dependent loads and with new patterns of operation on hydropower dams, with several starts and stops of turbines happening on a daily basis. The role of the turbines installed on run-of-the-river dams is nowadays indispensable due to providing fast reserve and ancillary services to the system. The hydropower plant (HPP) operational regimes follow the demand on the market; HPP's are used to cover variable part of the production (intermediate and peak load) and provide compensation for base load production in times of surplus of power in the system. Hydropower plants are paying the highest toll of this type of operation. Units that were in general designed to operate continuously in conditions of optimal utilization are being controlled on-line with multiple start-stop cycles and operate in off-design regimes. The sacrifice of turbines is already recognized in their shorter life expectancy; it was estimated that each start and stop procedure causes fatigue equal to 15–20 hours of operation [1]. Moreover, the warning signs of fatigue on the bearing concrete structure are recognized by some dam operators as well. In this paper, the full-scale issue of operational loads is adequately addressed by observing the dam's dynamic response right after the completion of the construction work, by the analysis of the operational patterns, and by implementing the measures gained by experience from similar structures, operating for years, where signs of an accelerated fatigue are discovered.

2. Ageing of dams

Any type of long-term behavior that leads to changes in dam properties with the passage of time and might affect dam safety, is described as dam ageing [2]. Based on ICOLD definition, ageing is defined as a structural deterioration that occurs more than 5 years after the beginning of operation. The deterioration that occurs before is associated with inadequate design and defects during construction or improper operation, where the effect of the exceptional events is excluded [3]. According to data of SLOCOLD, approximately 60% of Slovenian large dams were built before the 1980. In total, we have 42 large dams (according to ICOLD criteria); 3 historic dams (Ovčjaške klavže, Belčne klavže, and Putrihove klavže) are over 200 years old [4]. The mean age of modern large dams in Slovenia is 43 years; the oldest modern age large dam in Slovenia, Završnica, is 105 years old. The golden era of Slovenian dam construction was from 1950 to 1990. Fig. 1 presents the number of large dams in Slovenia according to the dam type. The most common dam type is concrete gravity (PG) and combined type of dam (concrete gravity and embankments – PG/TE). In total, we have 25 of such dams (18 PG and 7 combined PG/TE), together they represent 60% of Slovenian dam inventory. The mean age of concrete dams is 50 years, majority of them being built in the period 1954–1986, after the year 2000 we have built 8 large dams (4 TE, 1 PG, 3 PG/TE). Majority of large dams in Slovenia are built for hydropower purposes, while 80% of concrete dams are in hydropower use [5].

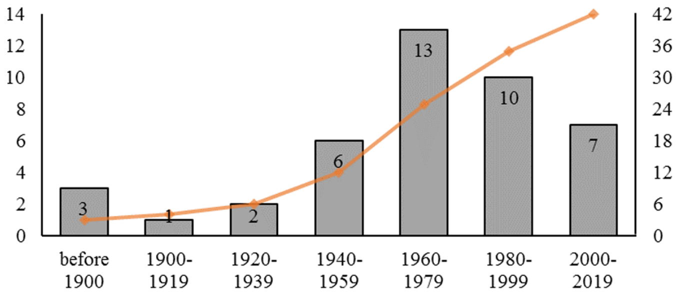

Fig. 1. Number of dams in Slovenia built since 1900

Dam ageing phenomenon is not unique to Slovenia, e.g. according to the United States National Inventory of Dams, more than 80% of their dams were built before the 1979, in Australia more than half of their dam inventory was built before the 1969, also in China the majority of dams were built between the years 1950–1970 [6–8].

3. Structural health monitoring of dams

Dam surveillance is recognized as one of the key activities in dam safety. Dam surveillance includes installation of the monitoring equipment, visual inspections, performance monitoring and functional testing, data management, and diagnostics. Surveillance serves both, to provide for early detection of anomalies and to provide knowledge on long term trends of the dam behavior. The aim of dam surveillance should be oriented towards monitoring of the identified potential failure mechanisms for the structure under observation and detection of warning signs linked to the mechanisms leading to failure, identifying potential deterioration, and acting before they become uncontrollable (or before the remedial work costs rise) [9]. Each dam is an individual case. Dam monitoring has a very long tradition, longer than other in civil engineering fields. However, nowadays in other civil engineering fields, e.g., bridge engineering structural health monitoring (SHM) programs are well established, while on dams in majority cases when (if) the dam is monitored the data is considered only when it is evident that something is not as it should be. In order to safely operate with the ageing dams, it is necessary to apply SHM activities also to dams. SHM is a multidisciplinary field connecting disciplines of structural vibration analysis, structural control, non-destructive testing and evaluation, material science, signal processing, sensors, classical civil and mechanical engineering [10]. The basic principle of a SHM system is presented on Fig. 2. We have to emphasize that in civil engineering, every project is unique and a unified general rule for perfect SHM system does not exist.

When talking about SHM, we always need to have the whole system in mind. The object under observation and the sensory system together also forms an integrated system, while the monitoring system is only as good as the installation. Every instrument, installed in the system, has a specific role and it should be selected and placed to assist in answering a specific question [11].

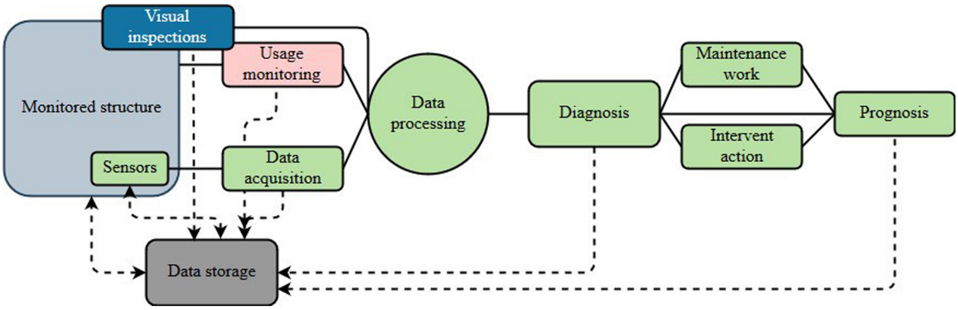

Fig. 2. Principle of a SHM system

After catastrophic dam failures in 1950 and later, the dam community became aware of the lack of knowledge on the potential failure mechanisms for all type of dams. Scaled shaking table tests were used to identify failure modes and to better understand the structural behavior especially during strong motion earthquakes [12]. On-site, full-scale non-destructive tests are another tool to prevent failure and to learn. Bukenya et al. [13] prepared a state-of-the-art literature review on health monitoring of dams with focus on in-situ applications. The first on-site, forced vibration tests (FVT) were conducted on on Wimbleball buttress dam, Llyn Brianne rockfill dam, and Baitings concrete gravity dam. Moreover, Deinum et al., (1982) [14]; Clough et al., (1984) [15]; Fenves and Chopra, (1986) [16]; Loh and Wu, (1996) [17]; Daniell and Taylor, (1999) [18]; Darbre and Proulx, (2002) [19]; Bukenya, Moyo and Oosthuizen, (2014) [20]; Hattingh et al., (2019) [21] demonstrated that the use of vibration test (ambient or forced) is an indispensable tool in structural identification and analysis of dams [14–21].

In Slovenia monitoring on large dam is a legal obligation for the dam owners. The existing monitoring system demands, that on all large dams, seismic monitoring needs to be established as well. For dams between 30–60 m in height, it consists of at least 3 accelerometers, where 1 must be placed in the foundation of the dam, 1 in a dam body above the foundation, and 1 on the free surface. Induced seismicity needs to be monitored by seismographs only on dams higher than 60 m. Large dams that are lower than 30 m need to have 2 accelerometers installed, one in the foundation of the dam and one on the free surface. Seismograph/accelerometer includes a velocity/acceleration sensor, time-series registrator, and a trigger for all 3 space axes. The equipment is installed in trigger mode with at least 5 s of pre-event memory [22]. Furthermore, Seismic network of the Republic of Slovenia (SNRS) has 26 stations, most of them of them are six channel stations equipped with broadband seismometer and accelerometer [23].

4. Pilot case

4.1. Lower Sava HPP cascading system

Our research focused on lower Sava River in Slovenia, where a cascading system of 5 run-of-the-river dams with limited retention capacity are built. The existing dams are presented on Fig. 3 and were built between the years 1993–2017: Vrhovo HPP (in 1993), Boštanj HPP (in 2006), Arto-Blanca HPP (in 2009), Krško HPP (in 2012), and Brežice HPP (in 2017). The dams have a similar design, they are all combined type of dams consisting of a concrete gravity and 2 embankments. Their main purpose is hydropower. In all powerhouses there are 3 Kaplan turbines of different types installed, they operate at 500 m^3/s rated discharge. Additional information on the units is available in Table 1. The production on Boštanj, Blanca, and Krško HPPs are remotely controlled from the control centre at Brežice. Vrhovo HPP is owned by different company and therefore has a permanent crew present on the dam site. Regular monitoring is established on all dams.

Fig. 3. Lower Sava HPP cascading system

Table 1. Summary of installed units in lower Sava cascading system

HPP	Turbine type	Number of units	Rated power [MW]	Rated head [m]
Vrhovo	Double-regulated, horizontal, bulb-type Kaplan	3	34.2	8.12
Boštanj	Double-regulated, horizontal, bulb-type Kaplan	3	32.5	7.47
Arto-Blanca	Double-regulated, vertical Kaplan	3	39.1	9.29
Krško	Double-regulated, vertical Kaplan	3	39.1	9.14
Brežice	Double-regulated, vertical Kaplan	3	47.4	11

4.2. The experiment

The experiment consisted of several phases, the major part of the experiment represented measurements of vibration on Brežice HPP. The experiment started already during the construction of the dam and lasted for 3 years, while the major portion for the vibration measurements were performed during the start-up tests of the hydro-mechanical equipment [24]. Vibration measurements were performed to detect ambient vibrations of the structure subjected to regular load during the specific life cycle of the dam. The dynamic monitoring of HPP Brežice started in 2016 with the first recordings before the mechanical equipment was installed and Sava River was still flowing through a diversion channel. These measurements were crucial for further diagnostic work, since they represent the reference (as built) state of the dam. This state is assumed as the state of the dam in sound conditions with the initial latent condition, i.e. with the initial micro-cracking supply, where the effects of pouring, curing and hydration of concrete are captured. The information on dam's initial state is crucial for any SHM; unfortunately, in majority of cases, it is unobtainable. The first recordings were performed in the powerhouse and in the first pillar in the overflow section. The dynamic properties of the structure were determined from the response to the excitation by the construction activities. In the next stage, the start-up tests of the mechanical equipment provided for the most extensive experimental phase.

Start-up test of the hydro-mechanical equipment were the most extensive period for the vibration measurements. During the half of the year testing period all representative operational and emergency manoeuvres on all units were tested, including the simultaneous load rejection on multiple units. The response of the structure was measured in 8 experimental points located at different structural parts in the powerhouse. Figure 4 represents an example of the measurements; presents typical time-series during the unit's start-up procedure, which can be detected in the structural response.

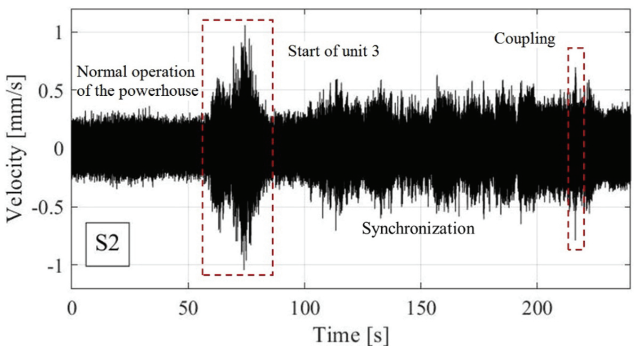

Fig. 4. Example of the measurement – start of the unit

Moreover, by obtaining and analysing operational logs from HPP located upstream from Brežice dam, we were able to identify the occurrence of various operational regimes during normal operation of the HPPs on Lower Sava River. Table 2 presents the results of the statistical analysis of operational logs obtained from Krško HPP obtained from October

2012 to May 2018. In all 5 years of operation of Krško HPP there was 88 situations where an emergency manoeuvre was necessary and in total 806 regular start-stop cycles, which are more or less evenly distributed among the three units (Unit 1, 0.3; Unit 2, 0.3; Unit 3, 0.4). Turbines have, in an average year, between 44 and 55 start-stop cycles of various lengths. The longest continuous operation recorded was on Unit 1 and it lasted for almost 82 days (1,963 hours). The sum of workinghours of all three units per year is 16,492 h, which means that 60% of the time in the year the turbines are in operation. Only 2% of continuous operation on Krško HPP is longer than 1,000 h, while 90% of operation is of 300 h duration or less.

Table 2. Turbine operation on Krško HPP

Unit	Median [h]	Longest [h]	Start-stop [year]	Emergency stop [year]	Operation [h in a year]
Unit 1 Krško	67	1963	44	4	6573
Unit 2 Krško	34	1557	44	5	5009
Unit 3 Krško	23	1172	55	7	4911
∑ Krško	40	1963	143	16	16492

4.3. Proposal for the inclusion of dynamic monitoring of Slovenian HPPs

The proposal for the inclusion of the dynamic monitoring in regular monitoring activities of HPP is based on the experience gained from experimental work and following the recommendations from the literature. The aim of the proposal is to introduce dynamic monitoring, with minimal additional costs and if possible, with the extension of the use of the equipment already installed to monitor the behavior of the dam. These recommendations are specific for the run-of-river hydropower dams, since our aim is to observe the effect of operational loads on the structural ageing.

By observing the vibration of the structure, we can estimate the condition of the built-in material. Every structure has unique modal characteristics and its unique vibrational signature that change only in case when the structure's mass, stiffness, or geometry is altered. Therefore, if the structural damage causes a decrease in stiffness, the vibration patterns and modal "fingerprint" of the structure will change as well. In theory, if we know the response of the system in sound state, with comparison of the two states, the observed changes in modal properties are indicators of structural damage. By performing a long-term vibration monitoring and observation we can therefore actively assess the condition of the dam structure. Due to the operation with dams, the structure is always subjected to some excitation force (operation of turbine, reservoir, etc.). Therefore, monitoring of vibration can be implemented without the disruption to the regular operation of the dam, since for structural diagnostic only ambient vibration tests (AVT) can be used. AVT do not cause disturbances to the normal operation and the measured response describes actual frequency content representative for the structure. AVT is more appropriate for global application, while the use of forced vibration tests should be considered once we detect the deterioration processes have caused damage [25–27].

On the example of the Lower Sava River dams, we are proposing the following. On the existing dams there are already 2 accelerometers installed in the pier in the spillway; one in the crest and one in the foundation level. An additional accelerometer is installed in the proximity of the dam structure, and in the area, there are also 7 seismic stations that belong to the national seismic grid. The data from national seismic grid reveals there are a few local seismic events in the area every year. These events were recorded only on the national seismic stations. In a 2-year long period (2017–2018) there has been 15 local earthquakes recorded with magnitudes from 1.1 to 2.9, duration of 9–40 s, epicenter depths of 4–25 km, and dominant frequencies in the range of 4–20 Hz. Unfortunately, none of the accelerometers installed on the dams were activated during local seismic events. The accelerometers installed on dams are activated in trigger mode, while their threshold is set to high to activate them during local earthquakes. The first recommendation is to reconfigure the settings of the accelerometers, the recordings during local earthquakes would provide useful information on SHM, they could be also activated during flood waters when spillways are operating. Moreover, we also suggest the use of vibrometer, a portable device to measure structural response, for additional vibration monitoring [28].

Furthermore, additional accelerometers should be installed in the powerhouse; we suggest at least 5 more. One accelerometer in each turbine shaft and 2 accelerometers more should be mounted on representative places in the powerhouse structure. Fig. 5. represents the situation in the powerhouse of Brežice dam, which has been subjected to extensive vibration investigation, that started already during the construction. The accelerometers must have their sensitive axis oriented perpendicular to the surface of the structural member and measure vibrations in the horizontal direction, while one accelerometer must be placed to observe vertical vibrations. The experimental points are the locations where structural vibrations were monitored using vibrometer. The vibrometer is still used on a regular basis,

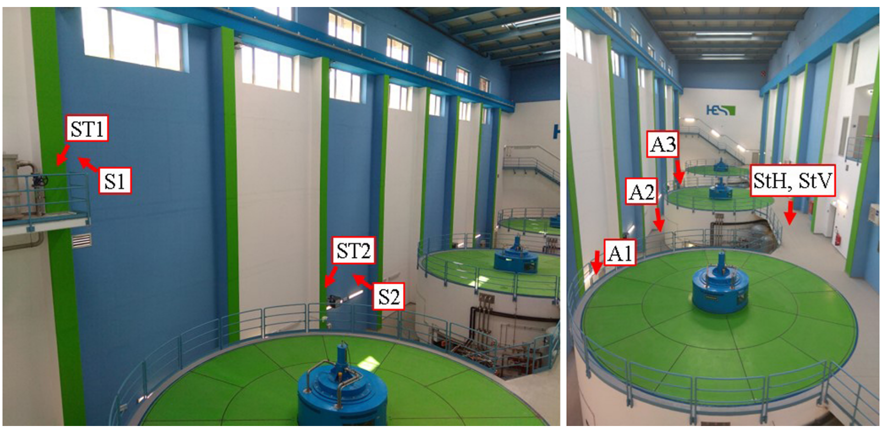

Fig. 5. Experimental point to measure vibration on Brežice HPP

or at least once per year, at the end of the cold part of the year. However, we recommend in depth vibration measurements using vibrometer to be conducted twice a year. The device can be used during all normal operating maneuvers [28].

5. Conclusions

In this paper we discuss operational loads, vibrations and ageing of concrete dams. Minimal extension of regular surveillance activities on the dams will substantially improve the operational safety of the dams and provide additional tool to dam management. The dam community has transitioned from the phase of building and designing the dams, to a phase of maintaining and extending their exploitation phase. A broad approach including an appropriate legislative framework and with application of SHM activities is necessary. While in case of building new dams, it is important that the activities of structural health monitoring initiate already in the design phase. SHM can help to minimize out-of-service time by applying automated and integrated system, to reduce manpower, and to reduce the room for human error. Service disruption due to regular periodic inspection can be reduced, while deterioration processes of the structure, caused by normal operation, are detected without any obstruction to the regular operation. Moreover, by observing the vibration of the structure we can actively monitor the aging process of the dam, and apply the maintenance and operation to extend the final age of the structure.

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