PROPOSAL FOR THE INCLUSION OF THE DYNAMIC MONITORING IN THE SCOPE OF REGULAR MONITORING OF SLOVENIAN RUN-OF-THE-RIVER DAMS

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ABSTRACT

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. The in-detail dynamic investigation is proposed to be done twice a year, or at least once at the end of the cold time of the year. 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 purposes. Basis of the system is the experimental work done in the last 3 years, which revealed the significance of vibration monitoring to observe the ageing phenomena and fatigue on concrete dams.

1. INTRODUCTION

According to ICOLD criteria we have 42 large dams (SLOCOLD, 2018). The most common dam type in Slovenia is concrete gravity dam (PG: 18 dams), while concrete and combined type of dams (TE/PG/TE) provide for 60% of dams in Slovenia. Majority of dams in Slovenia are built for hydropower purposes, since 80% of concrete dams are in hydropower use (Kyžanowski & Humar, 2018).

Figure 1 presents the time dynamic of large dam construction in Slovenia after the year 1900. Three historic dams (Ovčjaške, Belčne, and Putrihove klavže) are over 200 years old, while the mean age of modern large dams in Slovenia is 43 years. The mean age of Slovenian concrete dams is 50 years, majority of them were built in the period 1954–1986. After the year 2000 we have built 8 large dams. Similar situation is also elsewhere; dam ageing is a concern worldwide. 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 (Su et. al, 2013; ANCOLD, 2019; USBR, 2018).

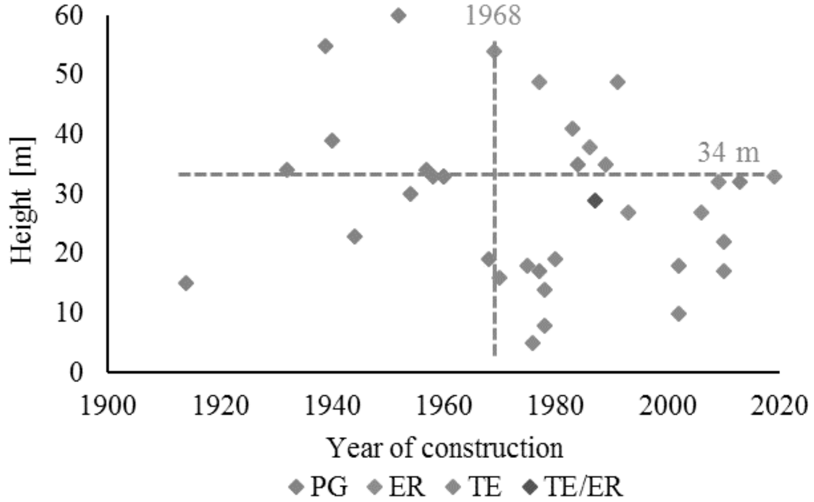

Figure 1 : Construction year of modern dams in Slovenia with respect to the structural height.

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 seismographs, where 1 has to 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 only on dams higher than 60 m. Large dams that are lower than 30 m need to have 2 seismographs installed, one in the foundation of the dam and one on the free surface. Seismograph includes a velocity 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 (Pravilnik o opazovanju seizmičnosti na območju velike pregrade, 2016). Furthermore, Seismic network of the Republic of Slovenia (SNRS) has 26 stations, most of them of them are six channel stations equipped with broad-band seismometer and accelerometer (ARSO, 2006).

In the past the majority of hydropower plants were operated locally. The crew consisting of operation, maintenance, and control personnel was present on dams every day. When operation gradually shifted from local to remote, simultaneously also the workforce was reduced. Not only operational workforce; the departments for design, planning, and maintenance of civil works have shrunken or were even cancelled. The tasks of structural and civil engineers were shifted to the operational staff, with mainly electrical engineering or sometimes mechanical engineering background. Therefore, the skill and knowledge of civil and structural engineers was partially transferred to the operational staff and also partially lost in transition. Nowadays the personnel on dams, also the personnel dealing with structural maintenance has mainly electrical engineering background, while the role of civil engineers have been attenuated. As a consequence, the concern for structural integrity does not have the same attention than it had the past. We believe that an inventory of ageing dams requires that more attention is given to the monitoring and maintenance activities, where a systematic structural health monitoring (SHM) needs to be applied. Moreover, we have to emphasize that a lot of HPP schemes are in operation for decades. Generations have coexisted with the reservoirs, bringing numerous ecosystem services. The ageing of dams also concerns the reservoir areas while emptying the reservoirs will have a broader environmental impacts. Furthermore, legislation needs to be updated as well, nevertheless in this paper we will focus only on the technical execution of SHM on our study case.

2. DAM AGEING

According to literature every year about 200 new large dams are built, while the intensity of dam construction was even greater in the past, we can assume that most of dams that will operate in the following decades were already built (Bernstone, 2015). A concrete dam built for hydropower purposes, survives some typical stages: design stage, construction, first filing of the reservoir, operation, repairs, and decommissioning. In the design stage, the characteristics of the dam are specified. The designed structure is a generic, idealized dam, with idealized behaviour. Once the dam is constructed and the reservoir filled, the as-built (real) values of the idealized parameters can be obtained. The first few years of dam's life are the most critical, the first filling of the reservoir presents a major transition in the local environment, the dam structure and waterways have to adapt to new load condition, while new equilibrium is established. The longest period in dam's life cycle is the operational phase, which is occasionally interrupted by regular maintenance periods. The duration of this period is a subject of quality and intensity of the deterioration processes. During this period, regulations concerning building construction, dam ownership, and monitoring operators can change. These changes, to some extent, have a direct or indirect influence on dam ageing (Tekie & Ellingwood, 2003). A hydropower dam built somewhere in the mid of the 20th century has most likely surpassed transition in operation, due to the reorganisation in the power supply market, which has a consequence on the hydropower dams to operate under less favourable conditions. Ageing occurs due to time related phenomena that effect chemical, physical, and mechanical properties of the materials (Smoak, 1996). Concrete gravity dams are especially prone to the following: alkali-aggregate reaction, chemical attack (chloride, sulphate), abrasion and cavitation, water seepage, concrete expansion and contraction, temperature cycles (e.g. freezing-thawing), and operational loads (de Wrachien, 2009).

In our study we are focusing on the operational loads and structural vibrations caused with operation. Concrete is composite material, moreover, mass concrete used in dam construction is very specific, since it has larger maximum grain size than usual concrete and is built in large volumes it is subjected to extensive early-age micro-cracking. Over time vibrations caused with operation of power plant can initiate further crack growth (fatigue cracking), at first on a microscopic scale and later with further accumulation of damage which evolves in exponential manner to the situation of reaching the critical point. The most vulnerable are points of stress concentration, joints, discontinuities, and nonhomogeneities. Crack growth after the crack initiation is slow at first due to gradual wear.

Operation of turbines induces vibration with very low amplitudes and a very large number of cycles with high frequencies in comparison to the natural frequencies of the structure. However, the continuous operation provides for high accumulation potential. Under the constant amplitude, the damage is slowly accumulating and eventually evolves into the exponential growth phase where the damage development becomes accelerated (see Fig. 2). The evolution of damage due to low-amplitude vibration is considered a slow process. However, when the fatigue evolves in a progressive phase, the process is accelerated, the progress of damage is visible and instabilities start to occur (not necessarily resulting in structural failure). Schematic representation of the fatigue damage accumulation normalised to the number

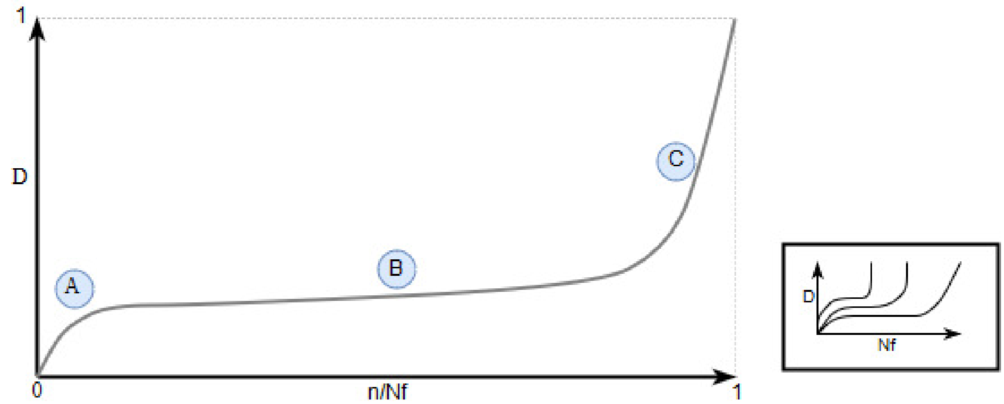

Figure 2 : Fatigue damage accumulation in concrete and scatter of damage accumulation.

of cycles to failure (N_f) is presented on Fig. 2, failure occurs when damage index (D) reaches value of 1. (Fritzen, 2006; ACI Committee 207, 2009; Lamond & Pielert, 2006; Japan Society of Civil Engineers, 2007).

3. DYNAMIC MONITORING

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 behaviour. 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 taking action before they become uncontrollable (or before the remedial work costs rise) (ICOLD Bulletin 138, 2009). 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 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 (Fritzen, 2006). The basic principle of a SHM system is presented on Fig. 3. 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 form 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 (ICOLD Bulletin preprint 180, 2018).

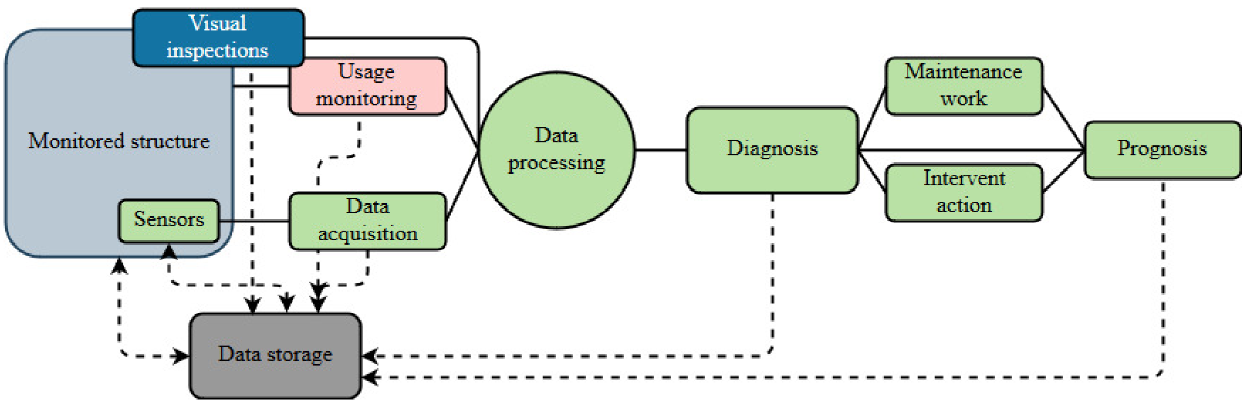

Figure 3 : Principle of a SHM system.

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 behaviour especially during strong motion earthquakes (Niwa & Clough, 1980). On-site, full-scale non-destructive tests are another tool to prevent failure and to learn. Bukenya et al., (2014) 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); Clough et al., (1984); Fenves & Chopra, (1986); Loh & Wu, (1996); Daniell & Taylor, (1999); Darbre & Proulx, (2002); Bukenya et al., (2014); Hattingh et al., (2019) demonstrated that the use of vibration test (ambient or forced) is an indispensable tool in structural identification and analysis of dams.

4. PILOT STUDY

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 were built between the years 1993–2017: Vrhovo HPP (1993), Boštanj HPP (2005), Arto-Blanca HPP (2008), Krško HPP (2012), and Brežice HPP (2017). The construction of the last dam in the system, Mokrice HPP, is expected to start in the following years. 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 centre at Brežice. Vrhovo HPP is owned by different company and therefore has a crew present on the dam site every day. Regular monitoring is established on all dams. Vrhovo reservoir represent a frontal pondage, and Mokrice reservoir after the construction of the last dam will represent the balance reservoir and the end of the scheme.

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

HPP	Turbine type	Number of units	Rated power [MW]	Rated discharge [m^3/s]	Rated head [m]
Vrhovo	Double-regulated, horizontal, bulb-type Kaplan	3	34.2 (3 x 11.4)	500	8.12
Boštanj	Double-regulated, horizontal, bulb-type Kaplan	3	32.5 (3 x 10.84)	500	7.47
Arto-Blanca	Double-regulated, vertical Kaplan	3	39.12 (3 x 13.04)	500	9.29
Krško	Double-regulated, vertical Kaplan	3	39.12 (3 x 13.04)	500	9.14
Brežice	Double-regulated, vertical Kaplan	3	47.4 (3 x 15.8)	500	11
Mokrice (TBC)	Double-regulated, horizontal, bulb-type Kaplan	3	28.05 (3 x 9.35)	500	9.47

4.1 Operational loads

Dynamic loading present throughout regular or exceptional operating regimes has a significant impact on mechanical properties of concrete gravity dams. Operational logs from Krško and Brežice HPPs were analysed. The data from both stations was obtained from the day of first operation to May 2018, Krško station started the operation in October 2012, while Brežice HPP in October 2017. Basic statistics from both station is presented in Table 2.

Table 2 : Turbine operation on Brežice and Krško HPP.

Unit	Median [h]	Longest [h]	Start-stop [per year]	Emergency stop [per 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
Unit 1 Brežice	14	460	77	10	5447
Unit 2 Brežice	15	640	77	5	5270
Unit 3 Brežice	17	381	68	7	5098
∑ Brežice	15	640	222	22	15816

The data from Brežice represents statistics of operational cycles from the periods during the start-up tests and trial run operation. During the testing period there is more start-stop cycles than later in operation, we can notice the median of operation on Brežice HPP is a lot lower than on Krško HPP. However, we can observe that the number of emergency operational regimes per year is similar on both HPP stations. 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 working hours of all three units per year is 16,492 h for Krško HPP and 15,816 h for Brežice HPP, 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.

Figure 4 represents the dynamics of start-stop cycles in the last decade on Vrhovo HPP. The mean number of cycles is 73 cycles/unit with standard deviation 20 cycles/unit. Statistically, Unit 2 has for 1/3 more cycles compared to the

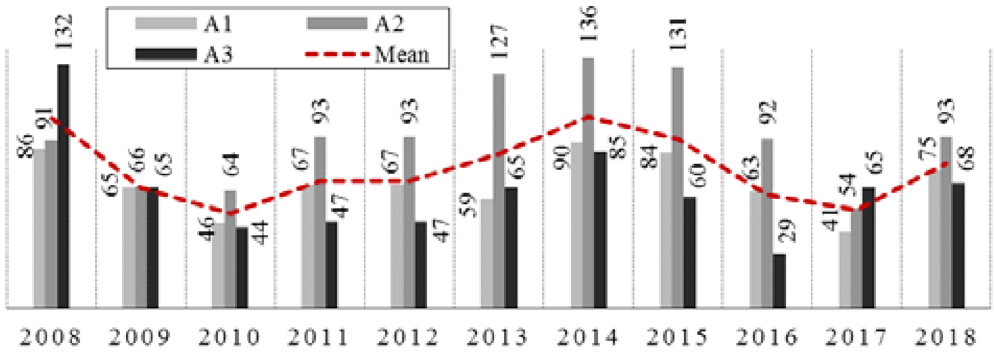

Figure 4 : Number of start-stop cycles on Vrhovo HPP in the last 10 years.

remaining two. Over the years, the number of cycles varied; the minimum was reached in 2010 and the maximum in 2014, when the total number of cycles doubled with respect to the 2010 situation. However, in the last 10 years we didn't observe any significant trend, the number of cycles remains more or less stable.

Measurements on Brežice dam during start-up tests revealed the vibration velocity amplitudes of structural vibration during operation of Kaplan turbines. Regular operation of turbines causes velocity oscillations with amplitude 0.5 mm/s, regular start and stop maneuverers cause an increase the amplitudes to approximately 1 mm/s and similarly also emergency brakes. Frequency spectrum analysis revealed as well that the exciting frequencies are close enough to the structural, which represent an issue on a longer time-scale (Klun et al., 2019).

5. THE PROPOSAL

The recommendations are based on the review of the state-of-the-art practice, in the literature, and on the lower Sava study case. 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 behaviour 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.

Generally, the extension of the current system includes:

- the use of the existing accelerometers installed on the dams in continuous mode;
- installation of additional accelerometers in the powerhouse;
- additional measurements of temperature, humidity, joint opening, dilatation behaviour, and
- seepage data;
- inclusion of data on manoeuvring with the hydro-mechanical equipment;
- additional prognostic (vibration) measurements;
- establishment of the statistical and numerical models;
- storage and analysis of data;
- interpretation.

Due to the operation there is always a sufficient amount of the excitation present on the dam. Therefore, we propose that only ambient AVT are performed. Forced vibration test require more time and a larger financial input, while 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 FVT should be considered once we detect the deterioration processes have caused damage (Bukenya et al., 2014; Rücker et al., 2006; Hsieh et al., 2006).

On the existing dams there are already 2 accelerometers installed in one of the piers 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, 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. This 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, epicentre 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. In our research we suggest to use vibrometer, a portable device to measure structural response. However, the use on the spillway section is limited only to situations with closed hydraulic gates, since the dam is designed that pillars are submerged during flood events (see Fig. 5). Since the neighbouring pillar is a standing point during the measurement, this limits the possibility for data acquisition.

Figure 5 : Situation at Brežice dam during normal operational regime and during flood discharge.

Additional accelerometers should be installed in the powerhouse; we suggest at least 5 more. One accelerometer in each turbine shaft (locations A1, A2, and A3 on Fig. 5) and an additional one placed on the south wall, we recommend location S2 as it is represented on Fig. 5. Fig. 6. 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. One accelerometer must be placed to observe vertical vibrations, on location StV, where vertical vibrations on Brežice dam were measured already during start-up tests. The experimental points are the locations where structural vibrations were monitored using vibrometer. The vibrometer is still used on a regular basis, 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 manoeuvres (Klun et al. 2019).

In the turbine also concrete, and ambient temperature must be monitored, while data on manoeuvring with the hydro-mechanical equipment should be logged and stored. Seepage data flow, which now is not measured, should be measured as well, the use of simple tipping buckets would be enough. Critical judgement of all the monitored data should be done on yearly basis. The work should be supported with numerical models. Data evaluation cannot be automatic; it must be a result of a sound engineering judgement. The data captured during the construction of Brežice dam, can serve as baseline also for structurally similar upstream dams, where signs of cracking are already visible.

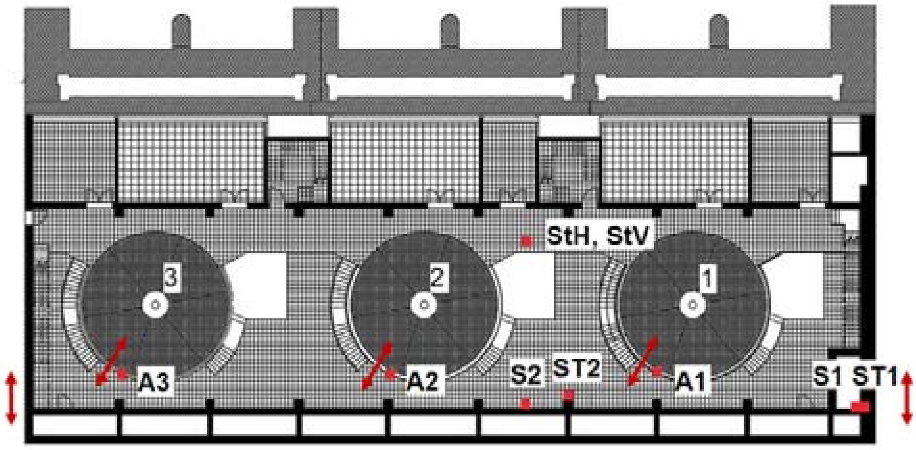

Figure 6 : Layout of the experimental points on Brežice dam in the powerhouse and numbering of the turbines.

When the building of Mokrice dam will start, it is crucial that monitoring activities start already during the construction, and that lessons learned from the upstream dams are incorporated in the design. The vibrations of the structure during the construction can be captured using vibrometer, while during the start-up test a combination of instrumentation should be used.

6. CONCLUSIONS

The primary goal of the research was to investigate the effect of operational loads on ageing of concrete dams. With the investigation on Brežice dam, which started already during the construction we investigated the behaviour of the system and recorded a reference state for the dam in an undamaged state. In our opinion this step is crucial, as well as it is crucial to continue with the investigation and expand it to the entire cascading system of structurally similar dams. The investigation also revealed that operation with turbines causes excitation in frequency spectrum that it is close enough to structural eigenfrequencies and is an issue on a larger time scale, while the cumulative effect is our major concern.

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 more or less 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 frameworks 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.

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