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ORIGINAL PAPER

Effect of environmental factors on modal identification of a hydroelectric dam's hollow-gravity concrete block

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Abstract
Dams are a type of civil infrastructure that can directly impact people's well-being, as their function is energy production, flood control, or water supply. Therefore, it is worth generating strategies to assess its current condition, since structural changes may occur during its useful life. One highly effective approach for evaluating the structural integrity of dams involves monitoring alterations in modal parameters. This method enables the identification of abnormal changes that may arise from structural degradation. Numerous studies have revealed the strong influence of environmental factors on modal parameters, resulting in variations unrelated to structural damage. This paper investigates the effects of environmental factors such as upstream water level and air temperature on the temporal evolution of the identified modal parameters of a hydroelectric dam's hollow-gravity concrete block. Modal identification is performed through an automatic procedure of estimating modal parameters to 30-min acceleration time series over 3 years of operation. Correlation analysis reveals a distinct relationship between the identified modal parameters and environmental factors. Changes in air temperature exhibit a direct proportional impact on natural frequencies, while fluctuations of the upstream level have an inverse effect. Furthermore, a time lag was observed in the natural frequencies concerning air temperature. Multiple linear regressions were fitted to mitigate the induced effects, incorporating as predictors the upstream water level and the averages of air temperature segments measured prior to the predicted frequency. A reduction in variability of more than 50% was achieved in an out-of-sample 8-month period for the modes linked to the natural frequencies most influenced by environmental factors.

Keywords Structural health monitoring · Modal identification · Concrete dams · Temperature time-lag effect · Upstream level

1 Introduction

Over the past 60 years, the construction of large dams has been on the rise due to population growth and the urgent need to manage finite water resources effectively. At present, the International Commission of Large Dams (ICOLD) maintains a record of 61,988 large dams constructed worldwide, boasting a combined storage capacity of about 8767 km^3 [1]. In addition to providing great benefits, these structures also represent a potential risk to the ecosystems and populations downstream. In particular, concrete dams can experience changes in their material composition throughout their lifespan due to physical, chemical, biological, and structural factors. These alterations can have a significant impact on both the performance and safety levels of the dams.

The monitoring of the structural performance of dams has been carried out over the years through auscultation.

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Instruments, such as pendulums, thermometers, extensometers, piezometers, and accelerometers, among others, are installed at key points of the dams. Decisions about structural health often rely on qualitative information from visual inspections and analysis of static data like deformation, stresses, displacements, temperature, and rotations [2–4].

The evaluation of dams' real behavior under vibrations can be traced back to dynamic field tests. Forced vibration tests (FVTs) were the initial tests performed with the aim of validating finite element models and predicting the structure's response to earthquakes [5–8]. Subsequently, ambient vibration tests (AVTs) have been introduced. This type of testing has emerged as the most practical dynamic test to be conducted on concrete dams [9] mainly for three reasons. Recent advances in vibration sensors allow the measurement of lower vibrations, as they present a higher resolution and lower noise. Second, there is a lot of theoretical background behind the development of methods for modal identification from only output data [10]. Third, there are some difficulties related to the excitement of the dam from external devices, such as their transportation to the dam location, frequently a remote place, and their position on the dam. Among the objectives of performing AVTs on dams, the most common has been to obtain experimental data to calibrate numerical models. Some studies on this subject are reported in [11–16].

Long-term AVTs have been employed in developing vibration-based structural health monitoring systems. These systems depend on the ongoing identification and monitoring of modal parameters. Under normal operating conditions, new data sets are obtained periodically and compared with an initial reference model. A significant change in these data may correspond to damage to the structure [17]. Large concrete dams are challenging due to their location in constantly changing environments. These harsh conditions can result in variations in modal identification that may not consistently indicate structural damage.

The literature reports that continuous ambient vibration monitoring programs have been conducted at the concrete dams Mauvoisin (Switzerland) [18], Hitotsuse and Ohkura (Japan) [19, 20], Fei-Tsui (Taiwan) [21], Cahora-Bassa Mozambique [22], Roode Elsberg (South Africa) [23], Chirkey [24], Cabril, Foz Tua, and Baixo Sabor (Portugal) [25–27]. These programs aim to track the temporal evolution of dynamic characteristics, primarily focusing on natural frequencies.

The assessment of identified modal parameters in dam infrastructure heavily relies on the water reservoir level. For instance, Oliveira et al. [21] discovered that a variability of 12 m in the reservoir water level of the Cahora-Bassa dam leads to a relative variation of 9% in the natural frequencies of the first mode and 10% in the natural frequencies of the second mode. Pereira et al. [25] found that the frequencies of the fifth mode of vibration of the Foz Tua dam decreased by about 13%, going from 6.67 Hz to 5.78 Hz in only 18 h with an increase in the reservoir level of about 2 m.

Many experimental and field studies have shown that temperature variation significantly affects the structural vibration properties of large civil structures [28]. Okuma et al. [18] reported that slow changes in natural frequencies of the Hitotsuse dam correspond to monthly and daily changes in surface temperature; however, it was impossible to quantify the variation due to temperature, as it is correlated with the reservoir water level. Ueshima et al. [19] found that the natural frequency associated with the vibration mode normal to the crest line of the Ohkura dam is highly correlated with the dam surface temperature, which causes an annual periodic variation between 2Hz and 3Hz. The authors emphasize that this variation is much larger than the observed when the dam has been subjected to strong earthquakes. After removing the influence of reservoir level on the natural frequencies of the Baixo Sabor dam, Pereira et al. [26] discovered that the frequencies' daily and seasonal variations are affected by air temperature, specifically for modal orders of 6 or higher.

Statistical models have been used in dynamic dam monitoring to predict structural responses. The models that have been adopted include power regressions (PR) [19], Gaussian process regressions (GPR) [22], and multiple linear regressions (MLR) [24, 26]. Statistical models based on MLR provide several advantages, including simplicity of formulation, rapid execution, and the ability to determine the contribution of each loading action to the dam response [29].

In 2016, an accelerometer network was installed at the Itaipu Hydroelectric Dam located on the border of Brazil-Paraguay. Since 2018, acceleration data have been gathered every 24 h. This paper presents a study on the impacts of upstream water level and temperature on the identified modal parameters of a hollow-gravity concrete block. This concrete block is instrumented with two triaxial accelerometer sensors. An automated procedure based on the automatic interpretation of the stabilization diagram from the Covariance Driven Stochastic Subspace identification (SSI-Cov) is used to obtain a new set of modal parameters every 30 min. Tracking these parameters over 3 years allows for the observation of both daily and seasonal variations in the dam's structural dynamics. In that sense, the main contributions of this research are summarized as follows:

- A methodology developed by the authors [30] for automatic operational modal analysis is tested on a real dam structure. This methodology relies on the SSI-Cov method and utilizes stabilization diagrams to identify the structure's modes.

- The influence of water level and air temperature on the modal identification process for the natural frequencies and damping ratio in a hollow-gravity concrete block is reported.
- A statistical procedure for mitigating the influence of environmental factors on the natural frequencies of the analyzed block is described.
- The importance of considering time lags in the modal identification of the block is discussed, stemming from the slow heat propagation in massive concrete dams.

2 Case study: the Itaipu hydroelectric dam

2.1 Dam and instrumentation description

The Itaipu Hydroelectric Dam is located on the Paraná river, on the border between Brazil and Paraguay. Twenty generating units provide a maximum capacity of 14,000 MW, making it one of the largest renewable energy generators in the world. With an extension of 170 km and a flooded surface area of 135000ha, Itaipu supplies about 10.8% of energy in Brazil and 88.5% in Paraguay.

The Itaipu Dam is 7919 m long with a maximum height of 196 m. The construction began in 1975 and began operations in 1984. Other details of the dam can be found on Itaipu's website [31].

Figure 1a shows the general scheme of the project. The structure of the Itaipu complex presents three types of dams: Earth-fill dam, concrete dam, and rock-fill dam. The concrete dam is divided into four parts, corresponding to the right-wing dam, the main dam, the connection blocks, and the bypass structure. The main dam comprises stretch F with 36 hollow-gravity blocks; the wing dam and the connection blocks, stretches D, E, and I with 91 buttressed blocks, and the bypass structure stretch H with 14 gravity blocks.

This paper studies the dynamic behavior of the concrete block F-17/18 located in the main dam as shown in Fig. 1(b). This dam has a length of 612 m at an elevation of 225 m

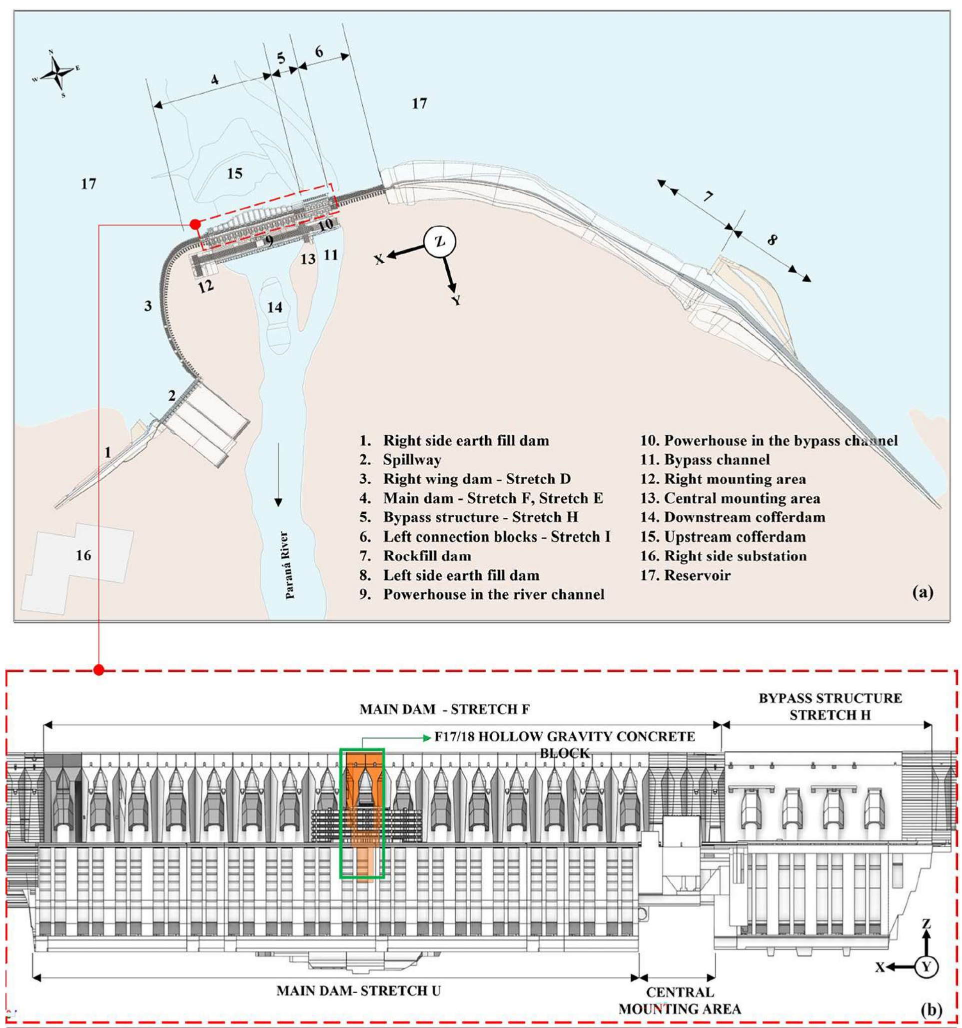

Fig. 1 **a** Itaipu project, overview. **b** Location of the F17/18 hollow-gravity concrete block in the main dam

(crest level). At the upper part of this dam, there are water intakes that control the flow of water from the penstocks to a spiral casing, where the kinetic energy of the water flow rotates the turbine of the generating units. These characteristics can be seen in Fig. 2 of the cross section of the concrete block F-17/18.

Itaipu technicians are assisted by 2218 instruments (1362 in the concrete and 856 in foundations and earthen embankments), of which 270 are automated. Figure 3 shows the accelerograph network installed in 2016. The network comprises seven stations distributed around the dam and one station installed in a neutral zone. There are five instrumented concrete blocks, including F-17/18. The sensors are Guralp Systems CMG-5TD digital triaxial force feedback accelerometers configured to continuously acquire acceleration signals at a sampling frequency of 200 Hz and produce hourly.gcf files (Guralp compressed file). For the dynamic monitoring of the concrete block F-17/18, data from the accelerometers ACL05-F18 located at an elevation of 144 m, and ACL06-F18 located at an elevation of 44 m were used. Both accelerometers are positioned with the N (North) component in the longitudinal direction of the ridge and E (East) in the downstream direction.

2.2 A Python-based computational tool for automatic operational modal analysis

To automatically estimate and track the dynamic parameters of the F-17/18 block, a Python-code based tool was developed at the Competence Center for Dam Structures (EB. DT-FPTI) of the Itaipu Technological Park. This tool is adapted to the type of data generated by the Itaipu accelerographic network; therefore, it can be used for the automatic modal analysis of any of the concrete blocks of this dam as long as adjustments are made to the input parameters of the programmed routines. In Fig. 4, the approach used in this application is presented. A more detailed description of this procedure can be found in [30].

The time-domain covariance-driven stochastic subspace identification method (SSI-Cov) has been widely used for continuous dynamic monitoring of large civil structures [32–36]. One of its advantages is the simultaneous identification of several modes. Stabilization diagrams are constructed after applying the method for different model orders, allowing the different modes of the system to be visualized as well-defined vertical columns. The automatic OMA procedure consists of the automatic interpretation of the stabilization diagram.

This procedure starts with the pre-processing of the acceleration time series. A low-pass Butterworth filter

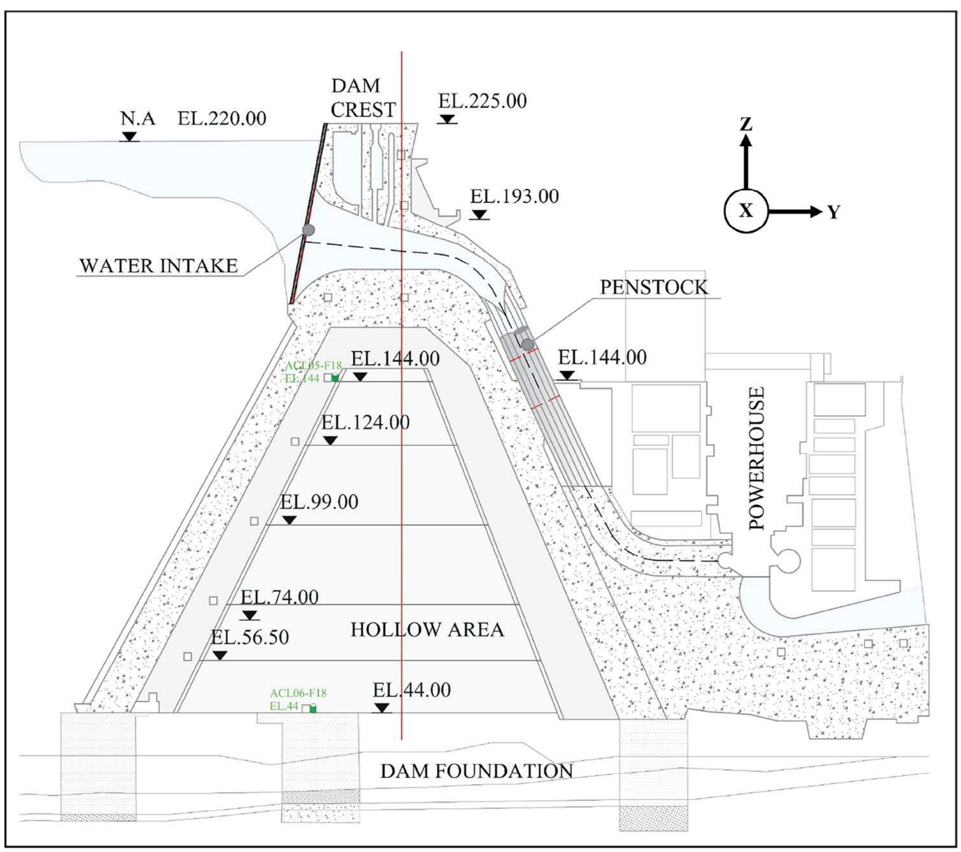

Fig. 2 Cross-section of the F-17/18 concrete block

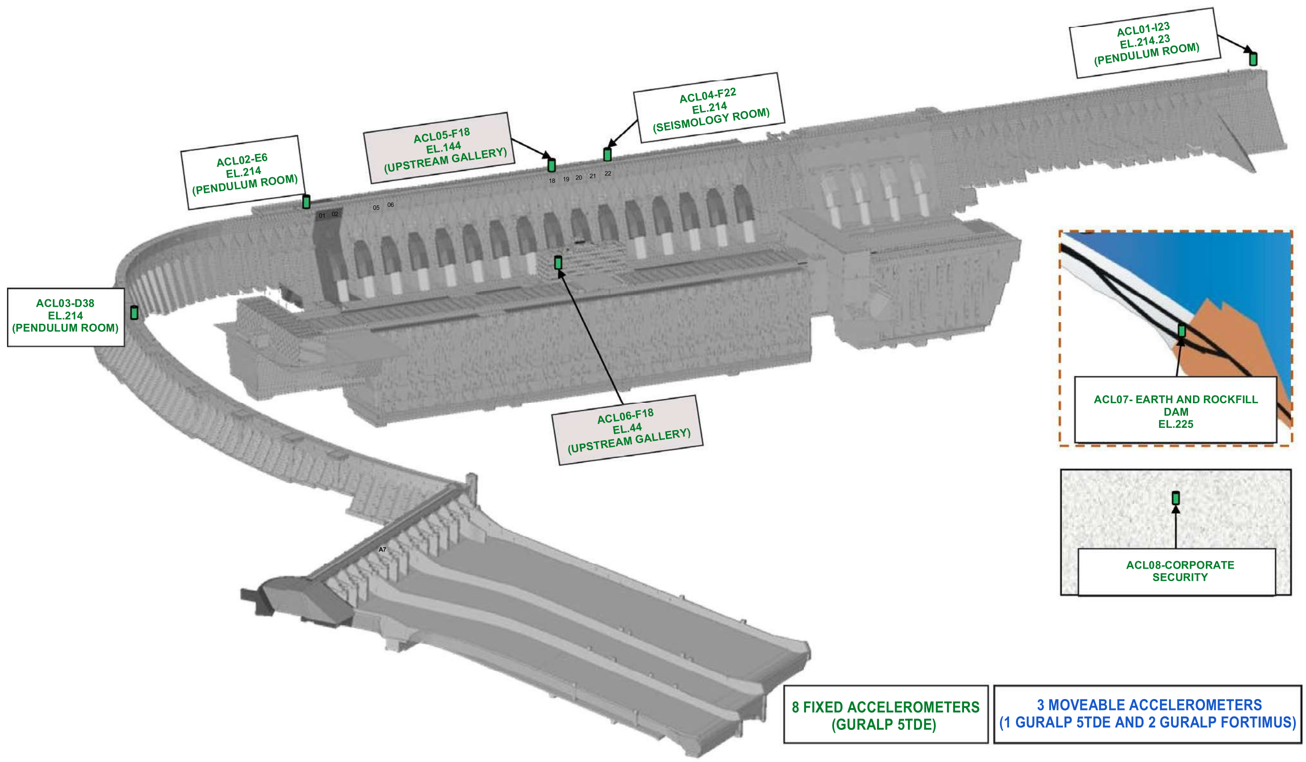

Fig. 3 Itaipu accelerograph network

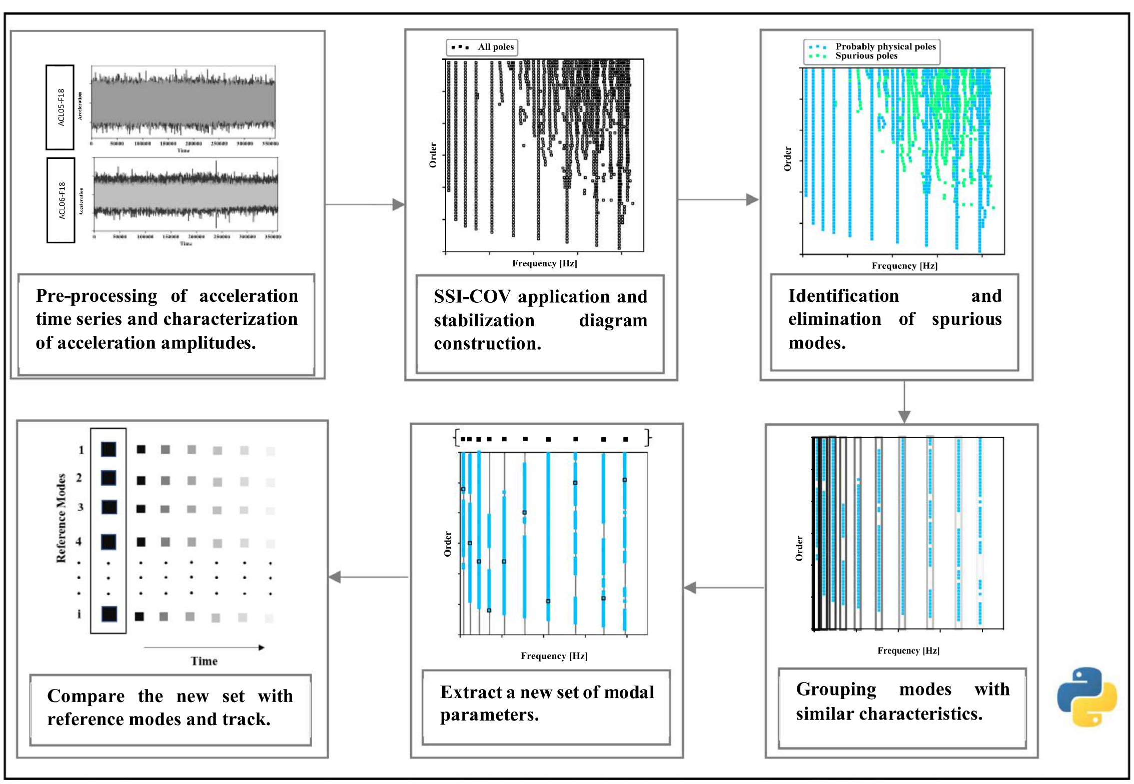

Fig. 4 Automatic operational modal analysis procedure