Introducing the concept of digital twin into dam safety management

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***Abstract*— Dams are vital infrastructure objects which must be maintained properly to avoid catastrophic failures or major accidents. Recent development of dam monitoring systems capabilities provides massive datasets that are overwhelming for traditional approach to dam safety analysis, which usually relies on expert's abilities to identify and undertake necessary measures in a timely manner based solely on observed variables. In most cases, the variables that may not be directly measured are of the biggest importance for structural safety (e.g., damage criticality, load capacity, etc.). These variables can be estimated using various numerical methods, such as finite-element method. The concept of "digital twin" applied to dam structures provides tools for the experts to assess various safety parameters of the dam in near real time by coupling numerical methods with live data from monitoring systems. This paper presents development of a dam safety management system, which serves to improve the maintenance, safety, and functionality of a dam. Dam safety management system is based on elaborate monitoring system and detailed FEM models of the dam and power plant which are used to provide estimations of structural behavior and implementation of various "what-if" analysis. The system also uses MLR models of various dam responses for quick checks of observed values. The integration of data from monitoring system with FEM and MLR models is achieved through efficient data management framework. Quality control of data is performed through fully automated process to provide inputs for data assimilation in numerical models. This way a digital twin of the dam is created that is used for dam safety assessment and evaluation of reactive and proactive measures.**

I. Introduction

Dams are an extremely important part of infrastructure offering indispensable benefits like irrigation, hydropower, domestic and industrial water supply, flood control, drought mitigation, navigation, fish farming, and recreation. Dams are objects that by their nature carry a certain risk to the surrounding area, so the issue of dam safety is of great importance. The concept of dam safety management can be improved by the existence of a software system, which will ensure the collection of all data that are part of the technical observation of the dam and their further analysis and engineering interpretation through mathematical models of relevant processes.

Today, there are 76 large dams in use in Serbia, according to criteria presented in [1]. They can be classified into two categories according to their purpose - electrical energy production (23 dams within Electric Power Industry of Serbia) and water resources management (water supply, irrigation, and protection from floods). The average age of these dams in Serbia is over 40 years, so there is a growing need for monitoring their condition to reduce the likelihood of damage, malfunction, and catastrophic discharge of water.

The concept of dam safety management can be improved by the existence of a software system, which will ensure the collection of all data that are part of the technical observation of the dam and their further analysis and engineering interpretation through mathematical models of relevant processes.

This paper discusses development of an advanced dam safety management system. The development was carried out over several years for multiple dams in Serbia, through collaboration between Jaroslav Cerni Institute (JCI), Faculty of Engineering, University of Kragujevac (FEKG), and Faculty of Science, University of Kragujevac (FSKG).

II. Research questions

The original goal of this dam safety management system was to provide conditions for the implementation of the strategy of proper maintenance of the dam, in order to increase its safety and functionality [2]. This system was supposed to manage not only information on safety-related activities, monitoring, and analysis, but also their correlation, and to provide feedback information on all interactions when required. General structure of this system is shown in Fig. 1.

However, some of the problems have been identified using the existing system of dam safety management, which includes:

- managing and processing large monitoring datasets, obtained from monitoring of the dam
- quality of collected data regarding their usability in numerical analysis.

These are the reasons why the existing dam safety management system needed to be upgraded by supporting two new approaches to processing and monitoring based on physics and a data-based approach. A physics-based approach involves linking sensor measurements with prior model prediction based on finite element models. A data-based approach implies continuous monitoring of the results of measurements and determination of conformity of measured quantities and their expected values obtained by statistical models. Similar approach has already been presented in [3] and [4], as a digital twin for bridge structures. A digital twin concept can be defined as a digital representation of assets, processes, or systems in the built or natural environment, which serves as real-time digital simulation model and is enabled by operative data acquired from monitoring, and data processing and

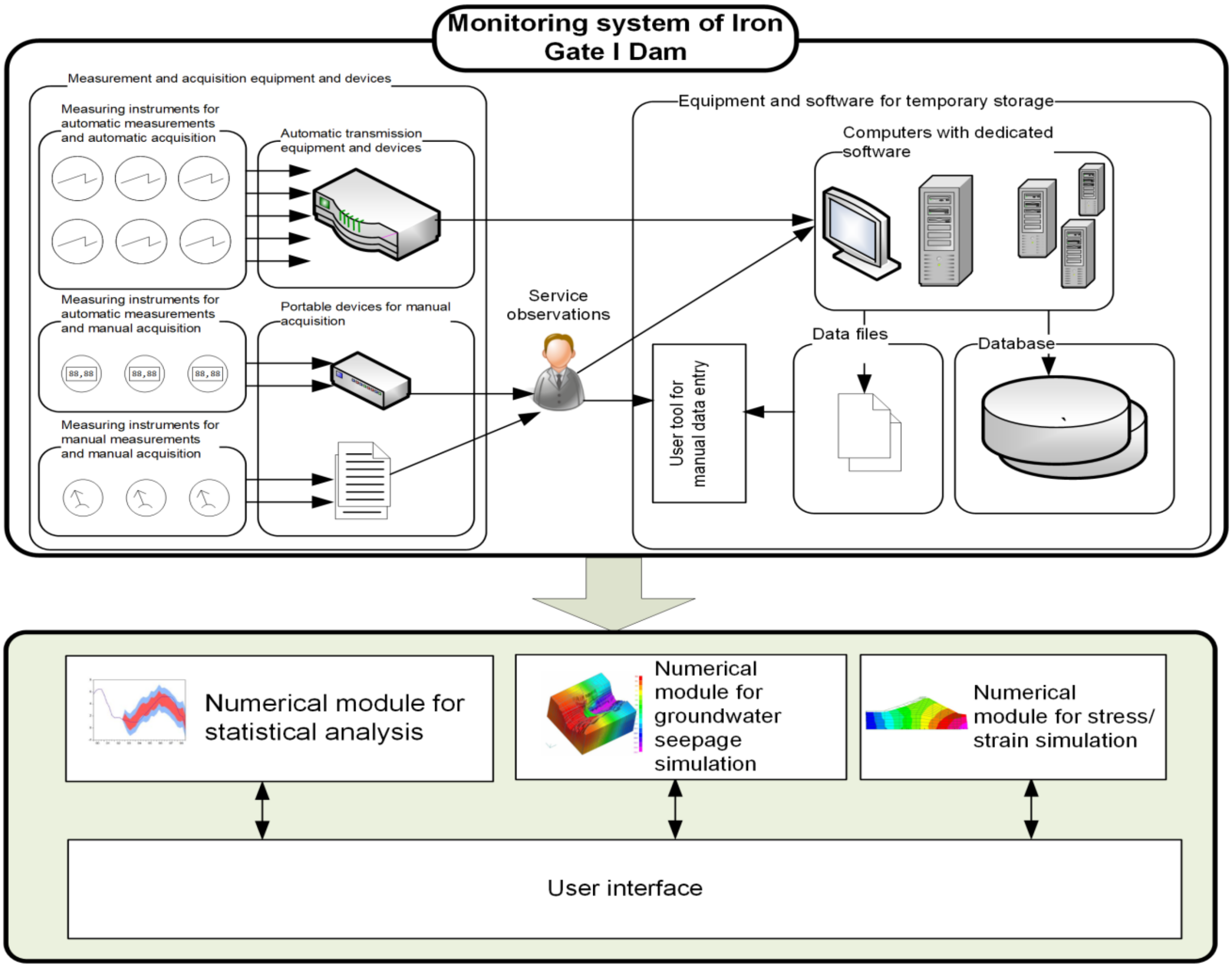

Figure 1. Original structure of Iron Gates I dam safety management system

interpretation routines. Various researchers have emphasized the quality of data as vital for digital twin applications in structural engineering [5], [6].

III. METHODOLOGY

Dam safety management is built upon detailed FEM models for seepage and stress analysis. Several dams in Serbia and neighboring countries have been modelled and incorporated into various dam safety management systems. The most complex model of Iron Gate I dam, shown in Fig. 2, consists of more than 1 million elements,

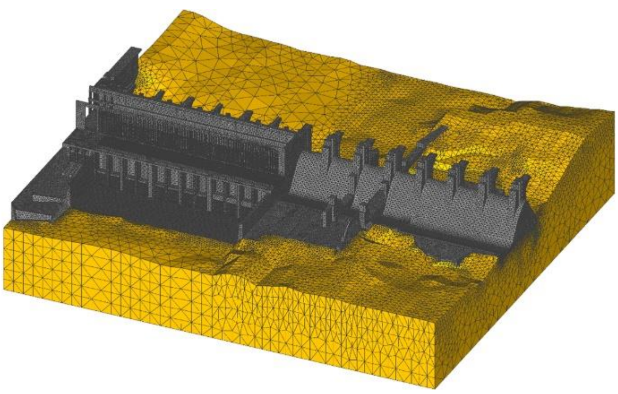

Figure 2. FEM model of dam and powerplant

and it is used for analysis of bedrock groundwater seepage, but also for the assessment of drainage system and performance of grout curtain and waterstops. Using historical monitoring data, several hundred material parameters of FEM model have been estimated through calibration process.

However, due to ageing of materials and various environmental factors (e.g., flood waves, earthquakes), many parameters require frequent recalibration. Since frequent recalibration is time-consuming and requires significant computational resources, a concept of data assimilation is used for periodical tuning of model parameters. Based on data acquired by monitoring system an multiobjective optimization problem is formed and solved using WoBinGO framework for parallel execution of the evolutionary algorithms, as given in [7]. The result of data assimilation is updated model that may be used for further analysis, such as: performance assessment of drainage system and waterstops, damage assessment, and what-if analysis (e.g., structural stability, rehabilitation planning).

As stressed earlier in this paper, data quality control is the one of the main prerequisites for successful data assimilation. Therefore, a data management framework has been developed and introduced in dam safety management system. The goal of data management framework is to obtain reliable data for data assimilation

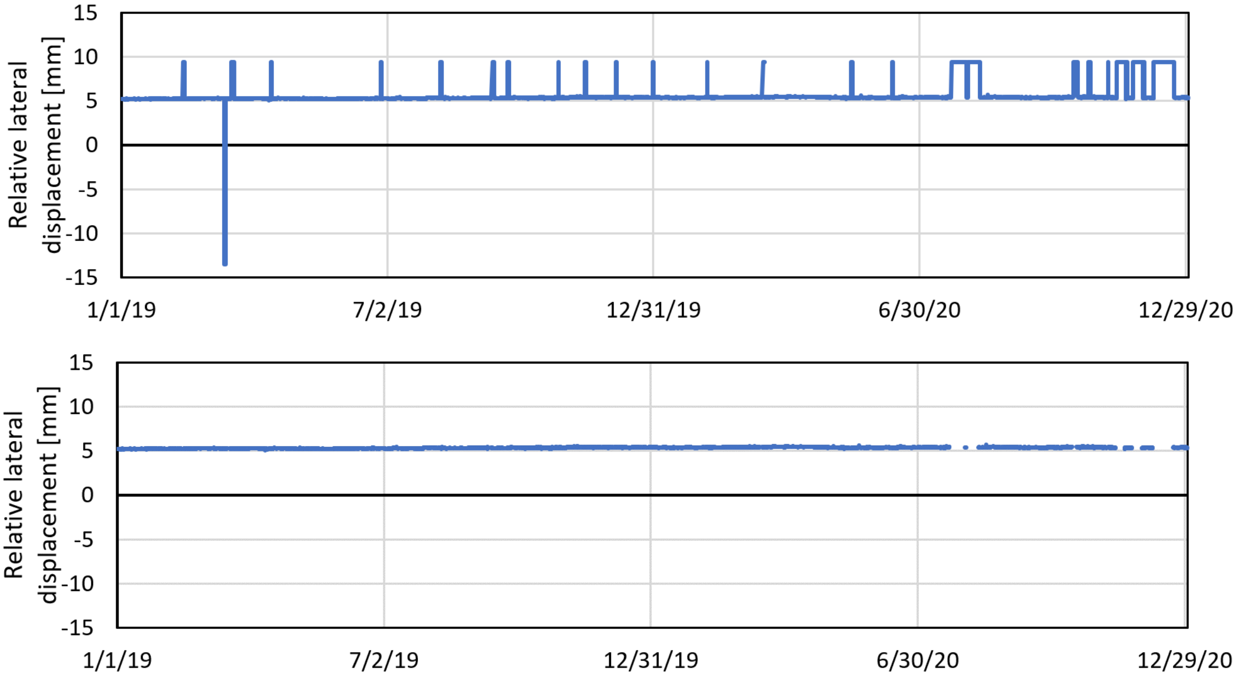

Figure 3. Raw data (above) vs. quality-controlled data (below)

and numerical analysis in timely manner, which is achieved through acquisition of raw data on measured values through ETL (Extraction, Transformation, Loading) processes, then through quality control of acquired data, and finally, through centralized processing of derived values.

All data from monitoring system must be processed by data management system before being used in data assimilation. Automated algorithm for data quality control is an integral part of this system. Apart from that, vital metadata on processes in dam monitoring and dam maintenance are included in data management system. Therefore, data assimilation process considers only data with satisfactory level of quality, as well as information on maintenance of the dam and adjoining structures.

An example of raw data vs. quality-controlled data is given in Fig. 3. The data in question is relative displacement on a gravity concrete dam. The role of quality control is to reduce erroneous data that may originate from faulty measurement equipment or noise.

By employing user-defined quality assessment schemas, raw data is processed, and every data value is assigned a quality mark, from 0 to 1, as given in [8]. Data values marked with 1 represent reliable data, while those marked with 0 represent erroneous data. There is also a user-defined setting for reliability threshold (usually, mark 0.5).

One application of quality-controlled data is to reduce the effect of erroneous data on derived values, such as daily means and extremes, by eliminating faulty data from processing. However, as shown in Fig. 3, this may create gaps in derived values, which may affect usability of such data in automated data assimilation. By using MLR statistical models which are based on historical data it is possible to perform automated reconstruction of missing values, as shown in Fig. 4. Values that have been reconstructed are shown in orange. In this specific example, both original and reconstructed data were used against values obtained from FEM analysis, so that data assimilation may be performed throughout the whole period. The process of data assimilation is tedious for such complex models, but by utilizing parallel execution on WoBinGO framework, it is possible to reduce computational times to less than a day, which can be regarded as near real-time for slow-changing processes in dam safety management.

Continuous use of upgraded dam safety management system capable of assimilating data from monitoring system in near real-time may be considered as an implementation of digital twin concept for dam structures.

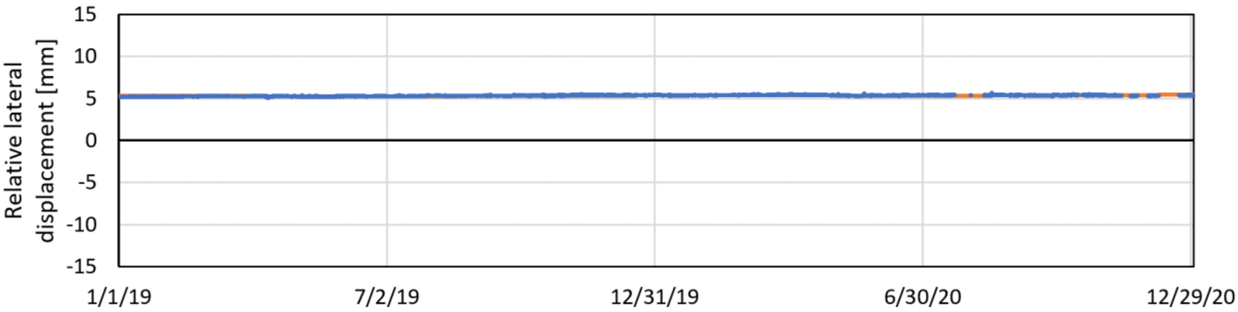

Figure 4. Reconstruction of missing data using MLR model (orange line)

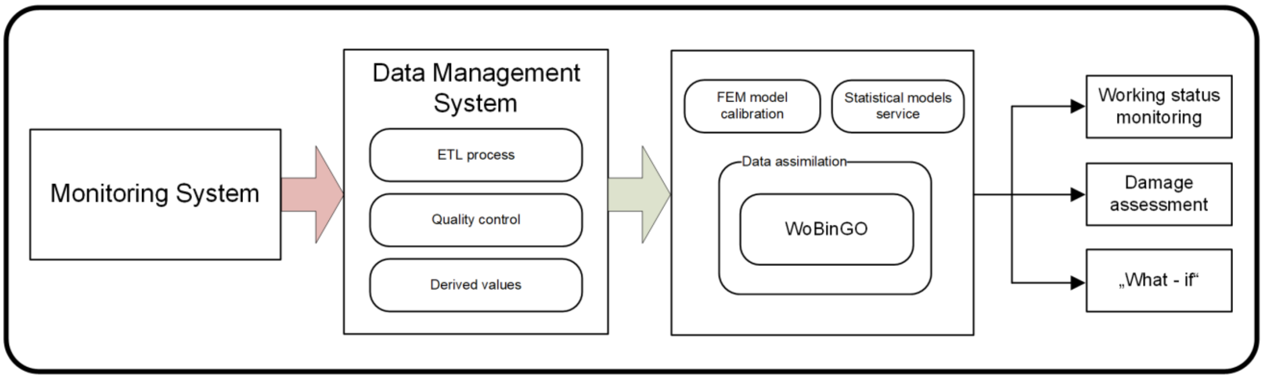

Figure 5. Dam safety management system for digital twin applications

Fig. 5 shows upgraded structure of dam safety management system.

IV. Discussion

Although the concept of digital twin usually assumes that the entire life cycle of a structure is digitized, from design to maintenance, in case of dam safety management system this is applicable to a certain point. Since most of the dams had been built decades ago, the design and the build phases have not been treated with the same level of detail as other phases of life cycle of a dam. Having in mind that dam safety management system is primarily designed to provide support in maintenance of the dam, the added value of data quality control and data assimilation may provide shorter response times for decision making regarding necessary maintenance or rehabilitation works. This has already been the case at Iron Gates I dam, where dam safety management system has been successfully used for assessment of performance of drainage system, grout curtain, and waterstops. The system enables the experts to produce reports on dam safety at any given time, and to plan maintenance in timely manner.

The estimated performance of waterstops, for example, may provide valuable information for experts to decide what kind of repairs are needed and where, while what-if analysis based on these estimations may provide how urgent these repairs may be. At the same time, experts are provided with tools to evaluate possible effects of repairs, and therefore can optimize the scope of the actions, by minimizing the consequences to dam and powerplant operation.

Further works on dam safety management system will be focused on application of machine learning in data assimilation of FEM models for stress analysis, since this problem is far more complex than it is in models for seepage analysis [9]. Also, machine learning may provide more robust methods of data quality control, thus providing timely and accurate data in heterogenous monitoring systems that are usually found at existing dams and structures [10].

V. Acknowledgment

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