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Construction of decision rules for early detection of a developing concrete arch dam failure scenario. A discriminant approach

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ABSTRACT

To improve the effectiveness of concrete dam safety control in real time, a method is presented for the construction of decision rules for the early detection of developing failure scenarios. The decision rules are based on the use of linear discriminant models developed with data obtained through mathematical models of the dam's behaviour. The aim is to combine the physical quantities measured by the automated monitoring system of the dam, appropriately weighted, into a new single index allowing the classification of the observations into one of two classes (normal behaviour and development of a failure scenario).

1. Introduction

The major potential modes of failure of concrete dams are related to natural phenomena such as a flood, rockslide, earthquake, and the deterioration of the heterogeneous foundations and construction materials [1].

Dam safety control activities require an accurate knowledge of each specific dam, with the purpose of defining and justifying the judgment about its safety. This task is mainly supported by cross validation between simulation models, measurements provided by the monitoring systems, and the parameters that characterise the dam's behaviour. The main issue is the assessment of the actual structural behaviour in real conditions, which can be used to detect any anomaly and/or malfunction in advance. The symptoms are not always timely detected in a concrete dam failure situation, leading to an uncontrolled progressive evolution of the problem until the verification of an accident or even the dam's rupture.

There are historical cases where abnormal dam behaviour was monitored before dam failure without successfully triggering alert to evaluate the population at risk, such as the cases of the Malpasset dam in 1959 [2,3] and the Vajont dam in 1963 [4,5].

Over the years, the evolution in the process of interpreting the physical quantities provided by dam monitoring systems is significant. Nowadays, Automated Monitoring Systems (AMS) have become a reality in several dams. These systems can be used to support the analysis for dam safety assessment in real time, but also lead to the increase of requirements related to the management, processing and analysis of large amounts of data. The development of internal early warning systems based on the automatic analysis of a large quantity of data in real time allows the possibility of early identification and notification of potential abnormal situations. However, the detection of abnormal behaviour in AMS is usually achieved through the assessment of each physical quantity in an independent manner, it not being possible to infer about the global dam behaviour. Thus, the next step is to implement decision rules that allow for the assessment of a group of physical quantities in order to detect early if the global dam behaviour is normal or in accordance with a developing failure scenario. In this context, dam behaviour is considered normal if it satisfies the following requirements: structural dam safety is verified, and the observed dam behaviour is in accordance with the expected dam behaviour based on mathematical or physical models, and past measurements under the same main loads (if available). Mathematical models are those most commonly used in the safety control of concrete dams. Within these type of models, two fundamental methods are usually used to predict a dependent variable (behaviour indicator) from other independent variables: the deterministic and the statistical methods. In addition to these two methods, there is another method, the hybrid method, resulting from the combination of the first two methods [6]. In deterministic methods, rheological laws of material are used (e.g. Finite Element or Discrete Element methods), and in statistical models, multiple linear

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regression analyses are performed on monitoring data without any consideration of rheological information. In this type of proposed study, the classification of the dam behaviour as normal can be a function of the intensity of the main loads. The motivation is to classify if the dam behaviour is in accordance (or not) with the expected behaviour under the loads whether it be usual, unusual, or extreme.

In this paper a proposal for construction of a decision rule through a Linear Discriminant Analysis (LDA) is presented. The LDA, developed by Fisher in 1936 [7], is a classification rule that considers that the data in each group follows a multivariate normal distribution. This type of analysis is used when the groups are known a priori, with the purpose of classifying new observations into a group [8].

The case study presented is related to the arch dam foundation failure scenario on the right bank of the New Alto Ceira dam, currently under construction. This study takes advantage of the use of the mathematical models developed in the design phase. In order to feed the decision rule with real measured data during the time period of normal exploitation of the dam, the data used was from the mathematical model that best represents the future data measured by the AMS of the dam. Thus, the decision rule can be used to perform dam safety control in real time, with respect to the early detection of developing failure scenarios previously analysed.

2. Structural safety control of concrete dams

Dam surveillance is the process of assessing the performance, safety and operability of dam and reservoir [9]. This process comprises three branches of activities, Fig. 1: (i) monitoring of the dam, its foundation, and appurtenant structures, (ii) visual physical inspections, and (iii) checking and testing of operational facilities.

Dam surveillance aims at managing the risk through the reduction of the probability of occurrence of poor performance or failure of a dam by providing a means of early identification of undesirable events that can possibly cause failure. The organisation of any surveillance process should thus aim to reduce the probability of failure as much as possible by [10]: (i) identifying of potential failure modes and providing a surveillance program to cover these, (ii) early detection of initial stages of evolving phenomena that can lead to failure mechanisms, and (iii) understanding the behaviour of the dam and its components using physical parameters and representative models.

The safety of the group formed by the concrete dam, the foundation, the downstream area of the dam, and the operational devices of the reservoir must be evaluated on their structural, hydraulic, operational and environmental components. With respect to the structural safety, the interpretation of the observed behaviour is based on the establishment of correlations between the loads, the structural properties, including material properties, and the structural response. These responses expressed in terms of displacements, strains, drained flow, etc., are compared with predicted values of the behaviour models, taking into account the observed loads and the material properties.

In the period of normal operation of a dam, the main actions and the structural response are well characterised and there is a strong functional relation between them. The development of behaviour models to represent this functional relation allows calculating predicted values based on the main loads, and comparing them with the observed values. If the evolution of the predicted dam behaviour (obtained by the model that represents the normal behaviour) and the actual behaviour (measured) is divergent, then the assumptions of the model have changed and the reason for this change should be identified to assess the consequences. Over the years, new developments in monitoring systems, namely through the implementation of automated data acquisition systems, have increased the capability of measuring the structural response and the main loads at dams, and with the desired frequency. Equally, new developments in information systems allow the person responsible for dam safety to have data access, to interpret the information and to be notified with early warnings about the dam's structural behaviour.

The early warning about the structural safety is currently performed individually for each measured response and does not inform if the dam's global behaviour is in accordance with a developing failure mode. The main concern of this research work is to propose a methodology that allows taking advantage of the global information of the automated monitoring systems for detection of a developing failure scenario.

The main failure scenarios are related to [11]: the dam foundation, dam materials, the dam's structural behaviour, the appurtenant works, or a combination of these scenarios. The main causes

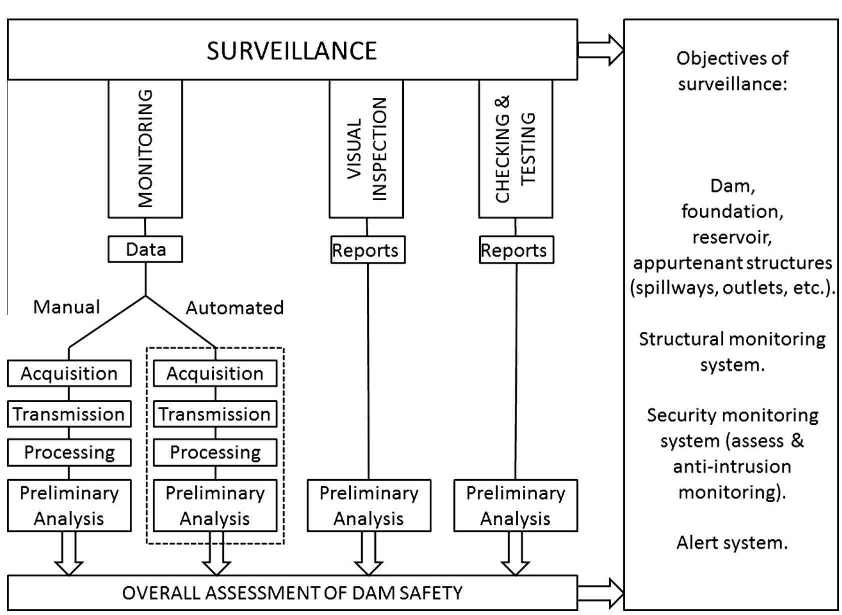

Fig. 1. Framework of surveillance, adapted from [9].