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Threshold Definition for Internal Early Warning Systems for Structural Safety Control of Dams. Application to a Large Concrete Dam

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Abstract

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 the cross validation between simulation models, measurements provided by the monitoring systems, and the parameters that characterize 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.

Over the years, we can verify a significant evolution in the process of interpreting the physical quantities provided by dam monitoring systems. Nowadays, automated data acquisition systems 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.

With the development of information systems to support the activities related to dam safety control, particularly the management of a large quantity of information, new challenges related to the management and analysis of information in real time are raised.

The implementation of an Internal Early Warning System (IEWS) based on the automatic analysis of a large quantity of data in real time allows the early identification and notification of potential abnormal situations and makes the person responsible able to focus on other activities related with the dam safety control of dams.

This paper addresses a proposal for an IEWS able to generate warnings in real time when non-accordance between observed and predicted values is verified. Subjects related to the definition of the thresholds for quantities measured by the monitoring system, as well as the notification process to the person responsible for the dam's safety control, are also discussed.

This paper presents the actual Portuguese experience. Aspects related with the requirements for the IEWS are approached. Threshold definition with quantitative interpretation models based on statistical methods, such as multiple linear regression models, and artificial neural network models, is discussed.

Keywords: Early warning system, Safety control of dams, Threshold definition, Information system.

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1 Introduction

Dam safety control is an ongoing concern for public and private entities, given the potential risks that the possibility of a dam break or other serious accidents represent, both in terms of human lives, economic costs, environmental damage, etc.

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 characterized 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 between the model prediction and the actual behaviour 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 take decisions, as quickly as possible.

Efficient performance can be reached with the aid of an IEWS, as a consequence of the necessity to assess a large amount of data in real time. In the context of this work, the main purpose of the IEWS is to notify the person responsible for dam safety control if the observed values are not in accordance with predicted values so that detailed analyses can be carried out.

2 Portuguese Experience

A measurement can be defined as the process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity. Measurement methods may be qualified in various ways, such as the direct and the indirect measurement methods. The indirect measurement involves a combination of direct readings from the measurement instrumentation.

There are two levels of validation for the measured data:

- The first one, at the level of the direct readings from the measurement instrument, based the acceptable range of measurement of the devices, and the past history of these readings when an enough time period exists.
- The second one, at the level of the final quantity pretended to be measure, taking in to account the structural dam behaviour.

The manual measurement of quantities for the behaviour assessment is usually possible in Portuguese concrete dams, and the validation of these readings, are carried out through an information system (IS), and in situ, by the comparison with thresholds and previous recent readings using a Portable Data Terminal (PDT), avoiding the majority of reading errors. In cases when the automated measurement is possible, the validation of the measurement is carried out by the IS. The following sections of this paper addresses only issues related to the second level of validation.

The National Laboratory for Civil Engineering (LNEC) has a IS, GestBarragens, a support system for monitoring, diagnosis and safety control of dams which was designed and developed using a modular approach, that can be accessed through a Web interface, Figure 1, (PORTELA et al. (2005), SILVA et al. (2005), SILVA et al. (2006)). Designed in Portuguese, its interfaces can easily be translated to other languages.

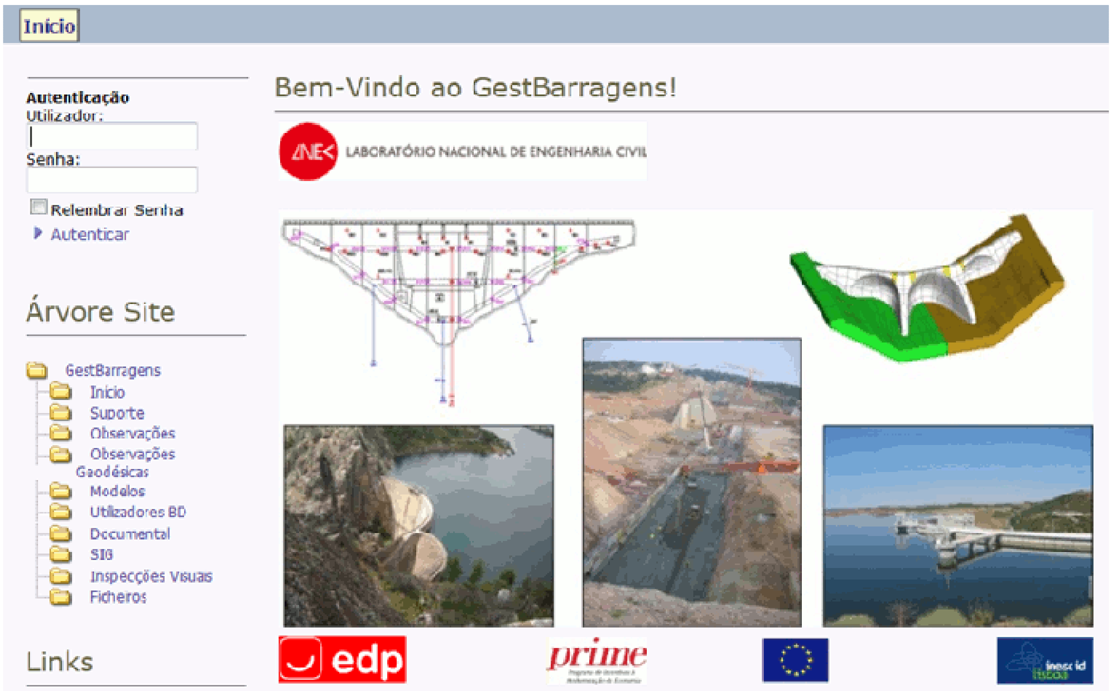

Figure 1 – Main GestBarragens interface.

Currently, GestBarragens includes a IEWS that allows the definition of thresholds, one maximum and one minimum for each month, based on the past history of the measured quantities. These thresholds can be edited for other different values considered adequate, Figure 2.

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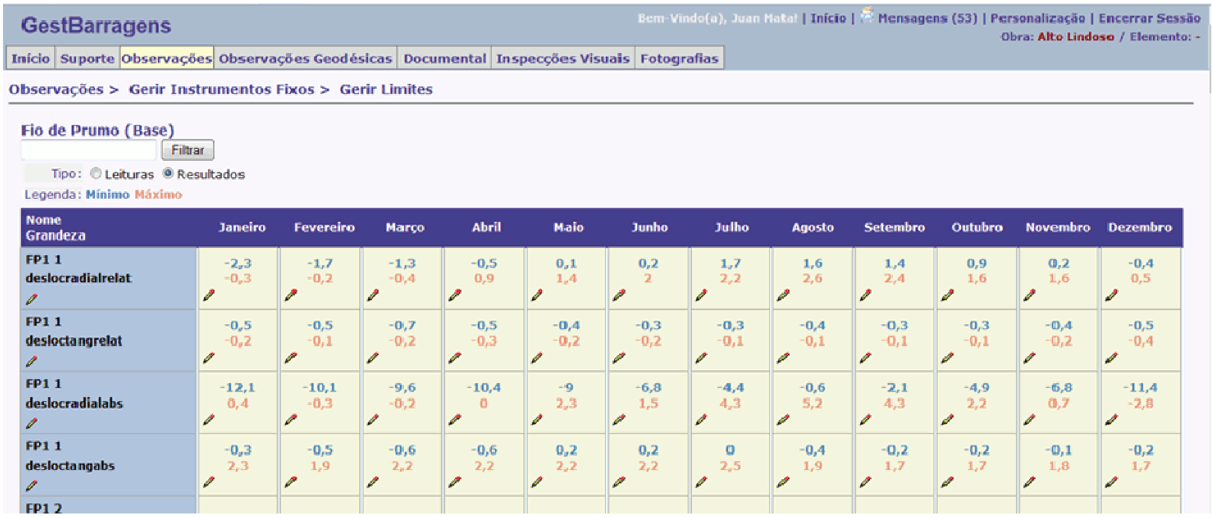

Nome Grandeza	Janeiro	Fevereiro	Março	Abril	Maio	Junho	Julho	Agosto	Setembro	Outubro	Novembro	Dezembro
FP1 1 deslocradialrelat	-2,3 -0,3	-1,7 -0,2	-1,3 -0,4	-0,5 0,9	0,1 1,4	0,2 2	1,7 2,2	1,6 2,6	1,4 2,4	0,9 1,6	0,2 1,6	-0,4 0,5
FP1 1 desloctangrelat	-0,5 -0,2	-0,5 -0,1	-0,7 -0,2	-0,5 -0,3	-0,4 -0,2	-0,3 -0,2	-0,3 -0,1	-0,4 -0,1	-0,3 -0,1	-0,3 -0,1	-0,4 -0,2	-0,5 -0,4
FP1 1 deslocradialabs	-12,1 0,4	-10,1 -0,3	-9,6 -0,2	-10,4 0	-9 2,3	-6,8 1,5	-4,4 4,3	-0,6 5,2	-2,1 4,3	-4,9 2,2	-6,8 0,7	-11,4 -2,8
FP1 1 desloctangabs	-0,3 2,3	-0,5 1,9	-0,6 2,2	-0,6 2,2	0,2 2,2	0,2 2,2	0 2,5	-0,4 1,9	-0,2 1,7	-0,2 1,7	-0,1 1,8	-0,2 1,7
FP1 2												

Figure 2 – Threshold definition interface.

The GestBarragens system validates all data that is changed or inserted. Users associated with the dams are notified when a warning is detected by the system. These messages are sent to an internal mail service of GestBarragens, Figure 3.

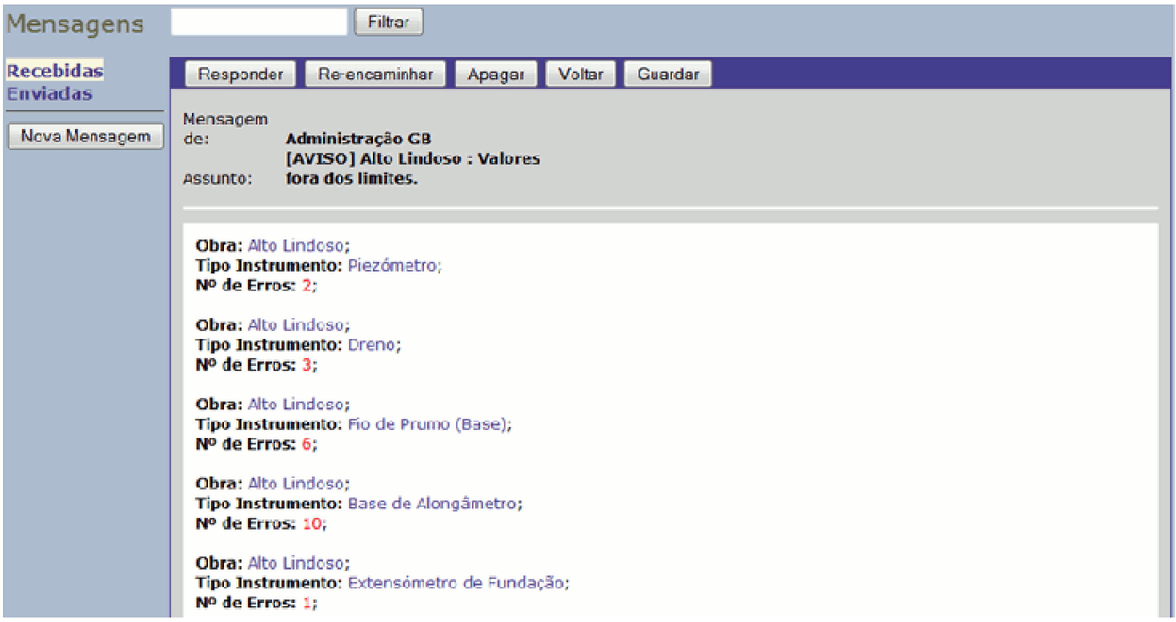

Figure 3 – Example of message application interface.

Improvements are being made in the IEWS of GestBarragens, so aspects related with the general requirements of the IEWS, the threshold definition, and other new features that will be implemented, will be addressed.

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3 Internal Early Warning System Requirements

The purpose of a real time IEWS is to provide an automatic mechanism to compare the actual against the expected dam behaviour. IEWS have to provide the ability to detect abnormal situations and initiate appropriate actions, like notifications, initiating the execution of activities related to the resolution of potential abnormal situations.

IEWS must be flexible to allow different processes related to the identification of abnormal situations and validation of the system operations. The detection of any abnormal situation should be assessed and reported. For each process, the definition of the responsibilities, functions, and procedures must be well defined. Operators must be aware of the risks derived from the loss of quality in fulfilling their role in the global procedures related to the safety control activities. In this work, three processes are suggested: routine validation, non-accordance measurement identification, and the predefined abnormal dam behaviour identification process.

- The routine validation process must be a scheduled routine with appropriate time intervals that aims to assess the validation procedure of results and the good performance of the notification system.
- The non-accordance measurement identification process aims to inform the person responsible of the quantities that are out of the limits previously defined as acceptable.
- The identification of an abnormal dam behaviour process is related to the occurrence of a set of measurements with non-accordance, previously defined. Such situations should initiate an integrated analysis of the various quantities including the potential causes and consequences.

The notifications must be sent to the people responsible for the dam safety via electronic mail messages or text messages to cell phones.

4 Threshold Definition

The thresholds that originate a notification of a non-accordance are the result of the comparison between a measured value against a predicted value increased by a factor which incorporates the uncertainties and the dispersion of data. The predicted values can be obtained using physical, mathematical or hybrid models, according to the existing knowledge of the phenomenon in question, the resources available and intended purposes (ICOLD (2003)).

Structural behaviour models are based on assumptions related to the type of analysis to be performed, the geometrical characteristics of the structures, the behaviour of materials, and the simplifications about the structural behaviour, among others. The uncertainties in the assumptions considered in structural dam behaviour models and the uncertainties inherent to the measurement process, and other, lead to the consideration of allowable ranges for the deviation between the measured values and the predicted values. In many

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cases, the selection of an allowable deviation can be based on a multiple of the standard deviation of the residuals obtained by the difference between the observed values and the predicted values during the analyzed period.

The classification of an observed value as non-accordance, according to this criterion based on standard deviations, does not mean that the integrity of the dam is threatened, but only that its observed behaviour does not correspond to expectations (ICOLD (2003)).

IEWS requires flexible thresholds that may be easily defined and implemented in the system. Apart from the type of criteria or model for the threshold definition, the division of the main loads (reservoir water level and temperature variations) in classes is proposed. In cases when the time effect is significant, it must be taken into account in the threshold by the increment of the respective effect on a limited time period.

In these cases, Quantitative Interpretation models based on statistical methods, such as the Multiple Linear Regression (MLR), have been widely used for displacement prediction of concrete dams, (ROCHA (1958), PERNER et al. (2001)).

A MLR model is a method used to model the linear relationship between a dependent variable Y that represents a quantity from the structural response, and one or more independent variables $(X_1, X_2,..., X_p)$ that represent the main loads (DRAPER et al. (1981)). These models consider that the effects during a limited time period at a specific point can be approximated by $Y = \beta_0 X_0 + \beta_1 X_1 + \cdots + \beta_p X_p + \varepsilon$, where ε is the error.

In matrix notation, the least squares estimator of β is $\hat{\beta} = (X^T X)^{-1} X^T Y$, where X is the vector of independent variables, the fitted model is $\hat{Y} = X\hat{\beta}$ and the vector of the residuals is denoted by $\hat{\varepsilon} = Y - \hat{Y}$.

If the hypothesis about the parameters of the MLR model are verified, then the main response variable Y corresponding to particular values of the independent variables $X_1, X_2,..., X_p$, can be predicted with a certain level of confidence.

If $x_0 = [1, x_{01}, x_{02}, \dots, x_{0p}]$, then the mean response at this point is $\hat{y}|_{x_0} = x_0 \hat{\beta}$.

A $100(1-\alpha)$ percent confidence interval on the mean response $\hat{y}|_{x_0}$ is obtained by Equation 1, where $t_{\alpha/2, n-p}$ is the t value for the Student's t-distribution with $n-p$ degree of freedom and n is the number of observations (MONTGOMERY et al. (1994)).

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$$\hat{y}|_{x_0} - t_{\alpha/2, n-p}\sqrt{\sigma^2(x_0^T(X^TX)^{-1}x_0)} \leq \hat{y}|_{x_0} \leq \hat{y}|_{x_0} + t_{\alpha/2, n-p}\sqrt{\sigma^2(x_0^T(X^TX)^{-1}x_0)}$$ (Equation 1)

For the threshold definition through the division of the main loads into classes, as suggested in this work, first, it is necessary to establish the classes and then to estimate the corresponding thresholds.

The prediction of quantities like relative displacements between joints, discharges and pressure with usual MLR models may not be possible due to nonlinearities, so the application of Artificial Neural Network models, such as Multilayer Perceptron Models (MLP), or even absolute reference values should be equally considered.

MLP models learn through an iterative process, by adjusting the weights so as to be able to correctly learn the training data and hence, after the testing phase, to predict unknown data, (FEDELE (2006), JOGHATAIE et al. (2009), YI et al. (2009), MATA et al. (2007), MATA (2011)). Figure 4 shows a typical MLP architecture with three inputs, one hidden layer and one output.

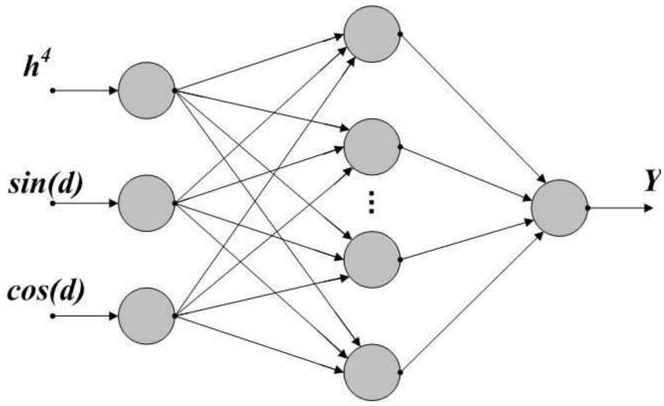

Figure 4 – Architecture of an artificial neural network.

If the hypothesis that the error is normally and independently distributed with mean zero and variance σ^2 is considered acceptable, the threshold can be estimated as $\hat{y}_0|_{x_0} \pm k\sigma$, where k is an integer.

5 Example of Threshold Definition

The choice of the most appropriate model for the desired purpose depends on the dam's life stage and on the information available. The IEWS addressed in this paper is intended to be used whatever the dam life stage.

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At the construction and first filling stages, the threshold definition is supported by deterministic models. At the normal exploitation stage the threshold definition can be supported by statistical models.

The majority of concrete dams in Portugal are in their normal exploitation stage. For this reason and to take advantage of the large amount of data recorded by the monitoring systems, the threshold definition based on historical data is presented in this work.

The example presented shows the methodology proposed for the threshold definition for horizontal displacements measured with a plumbline and the uplift pressure measured in a piezometer in the Alto Lindoso dam.

Alto Lindoso dam is a concrete dam exploited by EDP[1], a Portuguese company for electricity production. It is a double curvature concrete dam built in 1992 in a symmetrical valley in the North of Portugal, Figure 5. The dam is 110m high and the total crest length is 297m. There are three internal horizontal galleries across the dam and a drainage gallery close to the foundation, (EDP (1983)).

Figure 5 – Alto Lindoso dam.

The monitoring system of the Alto Lindoso dam consists of several devices (manual and automated) which make it possible to observe and measure quantities such as: concrete and air temperatures, reservoir water level, displacements in the dam and in its foundation, rotations, joint movements, strains and stresses in the concrete, and pressures and discharges in the foundation.

The monitoring system of the dam, installed during its construction, allows the manual measurement of quantities for structural dam assessment. In the recent past, an

[1] http://www.edp.pt

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Automated Data Acquisition System (ADAS) was installed but it is still in a testing phase. Figure 6 illustrates the ADAS of the Alto Lindoso dam. The manual measurement is also possible in those places.

The examples presented use data obtained manually because these observations have a larger period of observations than those obtained by the ADAS. However, the thresholds may be used to validate new measurements obtained by the two measurement systems.

Among the different loads acting on concrete dams in normal exploitation, it is usual to distinguish the hydrostatic load and the temperature variation as the most important ones.

For the presented example, the threshold definition was established for each month of the year, and four classes with equal amplitude were chosen for the hydrostatic load, represented by the reservoir water height.

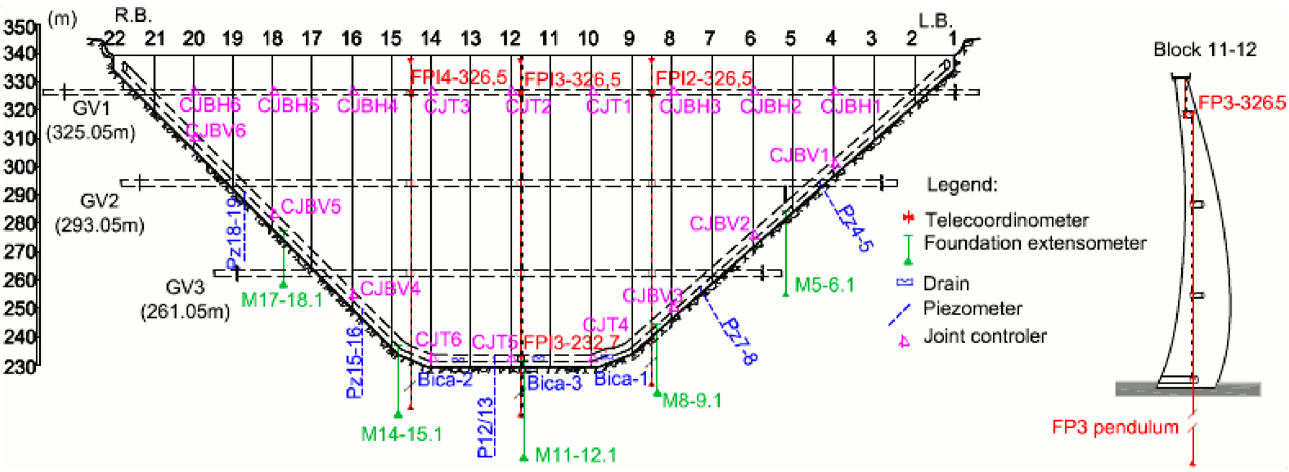

Figure 6 – Automated monitoring system of Alto Lindoso dam.

5.1 Division of Reservoir Water Level into Classes

The data used to determine the four classes with equal amplitude for the reservoir water level, for each month, comprise the period from January 2000 to December 2009 and the data considered for testing comprises the period from January 2010 to December 2011, Figure 7.

Figure 8 shows the values considered for the test for each of the four classes. During the time period of the test data, the reservoir water level exceeded the maximum or minimum limits obtained from the reference time period.

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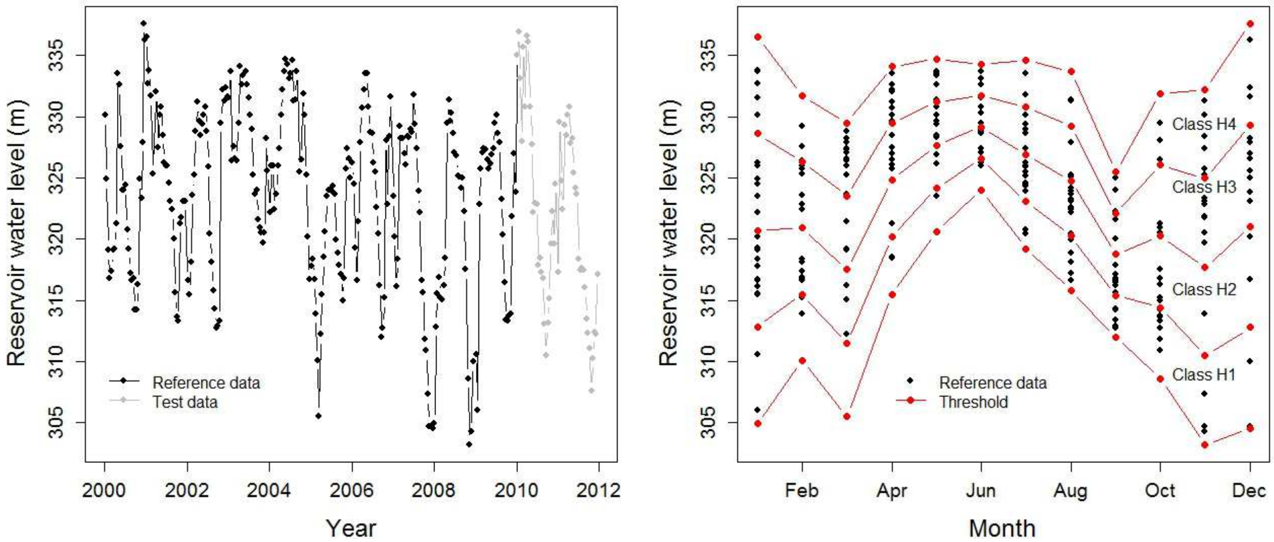

Figure 7 – Reservoir water level: reference data, test data, and classes.

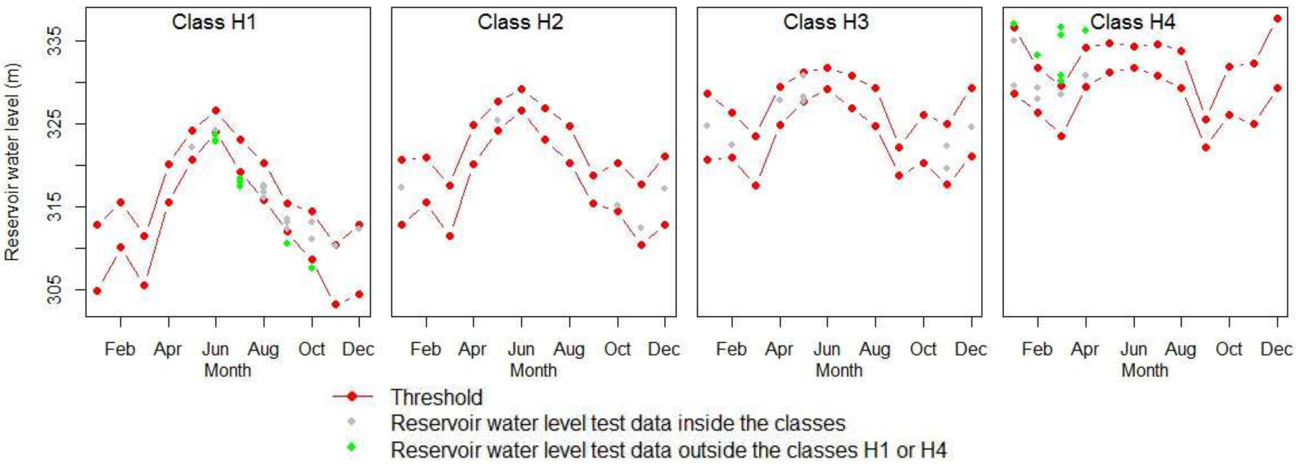

Figure 8 – Reservoir water level: classes and test data.

5.2 Horizontal displacements

Figure 9 shows the evolution of the radial displacements of plumbline FP3 at level 326.5m. In this case study, a MLR model was used for the prediction of the radial displacements. The displacement predictions were obtained as the sum of the hydrostatic pressure effect $\beta_1 h^4$ (where h is the reservoir water height that can vary between 0 and 110 m) and the temperature effect represented by $\beta_2 \sin(d)$ and $\beta_3 \cos(d)$, where $d = 2j\pi/365$ $(j = 1,2, \ldots 365)$, being j the number of days of since the beginning of the year. Taking into account the dam age, the time effect does not have significant importance in the time period examined by this study.

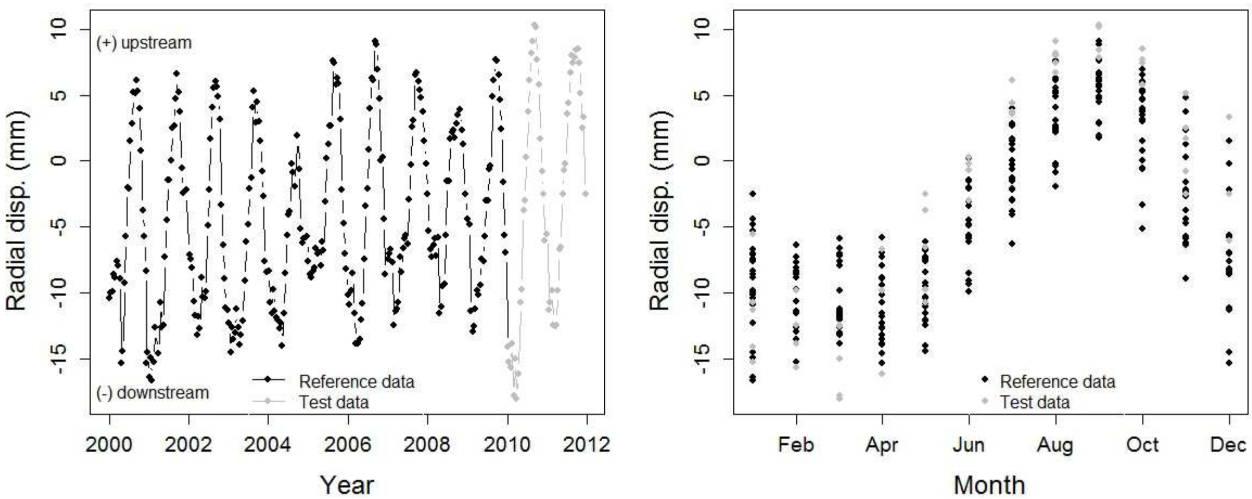

Figure 9 – Horizontal radial displacement of the FP3-326,5m: reference data and test data.

Figure 10 shows the adequacy of the classes, with a confidence level of 99.7%, and the corresponding test data. Note that although the reservoir water level data is outside the predefined classes, the corresponding observed displacements are majority inside classes H1 or H4.

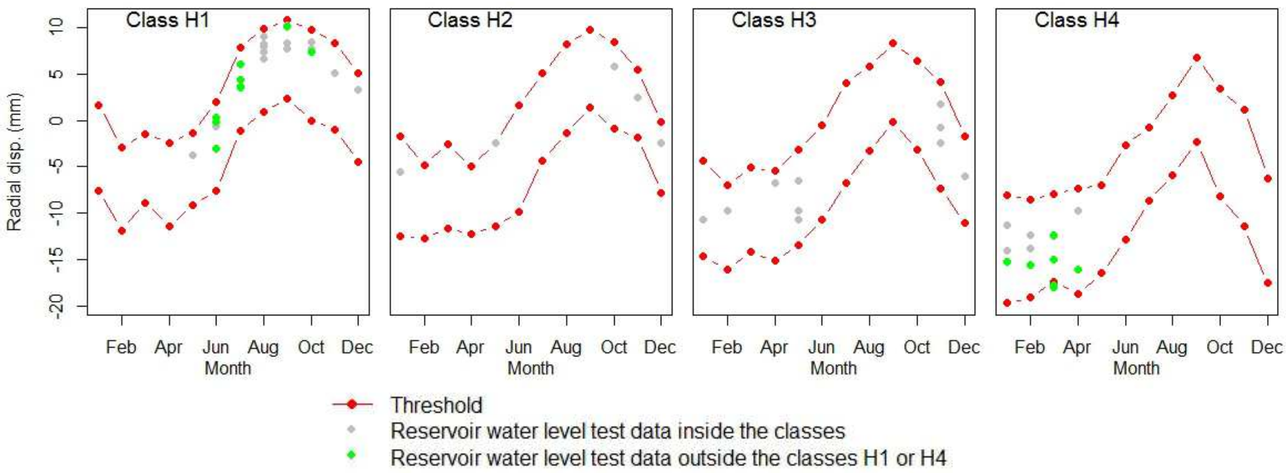

Figure 10 – Horizontal radial displacement of the FP3-326,5m: classes and test data.

5.3 Uplift Pressure

The definition of thresholds for the uplift pressure measured in the piezometer Pz12-13, Figure11, was obtained based on Artificial Neural Network models such as the MLP model.

The MLP model used in this case study consists of an input layer with 3 input parameters (to represent the hydrostatic pressure, h^4, and the temperature effects, $\sin(d)$ and $\cos(d)$), an output layer (to represent the uplift pressure) and one hidden layer. Every neuron in the network is fully connected with each neuron of the next layer. A hyperbolic tangent transfer function has been chosen to be the activation function for the hidden layer and the linear function for the output layer. The generalized backpropagation delta learning rule algorithm was used in the training process. The chosen network architecture has shown the best results, considering all the tested networks, from 3 until 30 neurons, at the hidden layer. To find the optimum result, 5 initializations of random weights and a maximum of 5000 iterations were performed on each MLP architecture. Once the model was obtained, the classes were defined based on predicted values added by three standard deviations of the residuals, Figure 12.

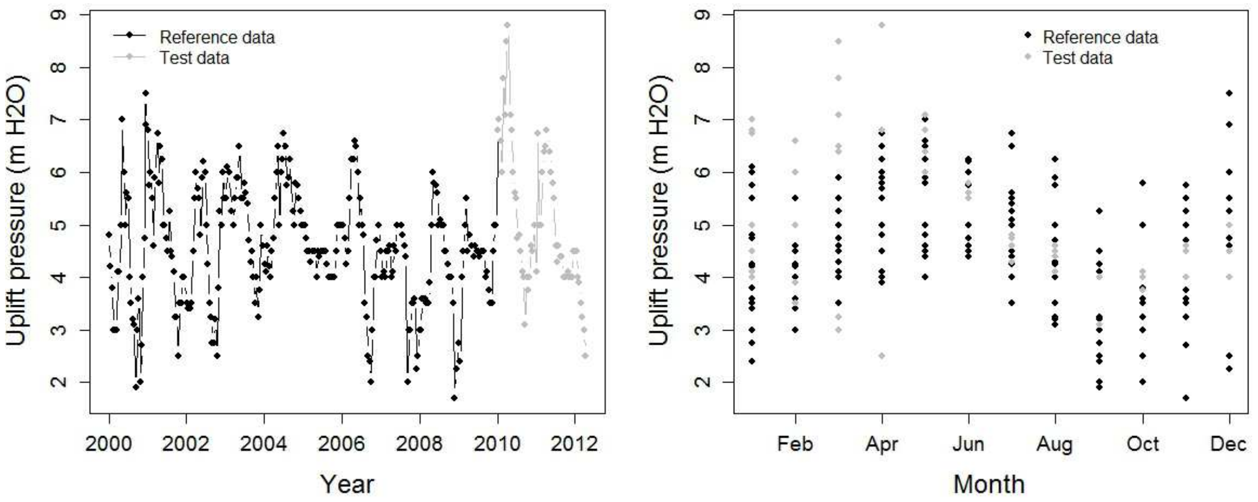

Figure 11 – Uplift pressure measured in Pz12-13: reference data and test data.

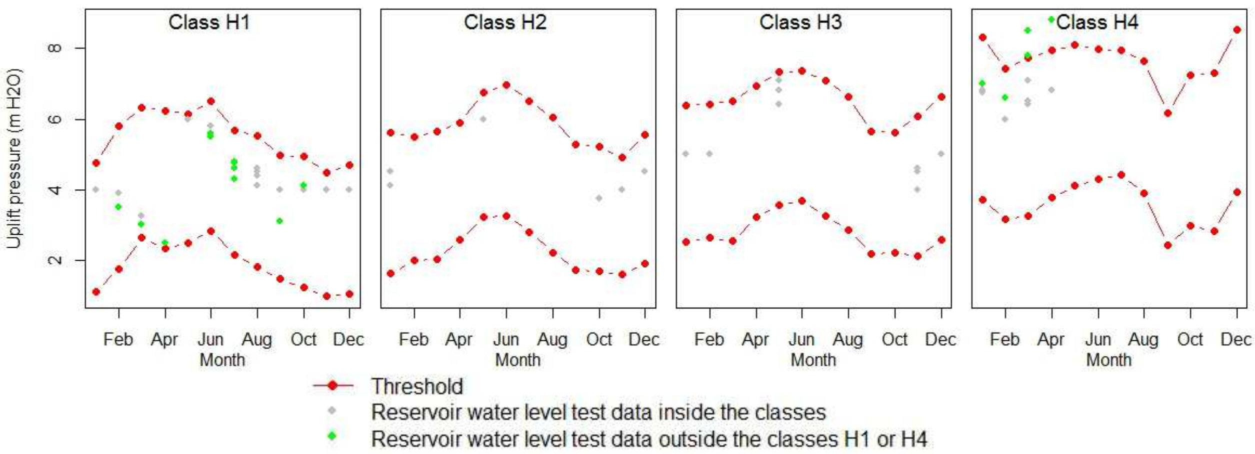

Figure 12 – Uplift pressure measured in Pz12-13: classes and test data.

6 Future Developments

The threshold definition of a quantity is a consequence of the main load history, the time period length, uncertainties of the measurement system, and the confidence level desired,

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among others. Therefore, further tests on other quantities, new data, and new dams, will be made.

Nowadays, GestBarragens allows the use of thresholds for one class of the reservoir water level and for each of the twelve months. The possibility of introducing divisions of the reservoir water level into classes, as presented in this paper, is the next step. The possibility of sending the notification via mobile phone will also be implemented and tested.

The graphical representation of the information when an abnormal situation is verified can be very important to the identification of the potential causes and consequences of a hypothetical problem. So, it is expected to develop a graphical interface to support an integrated analysis of all quantities, Figure 13.

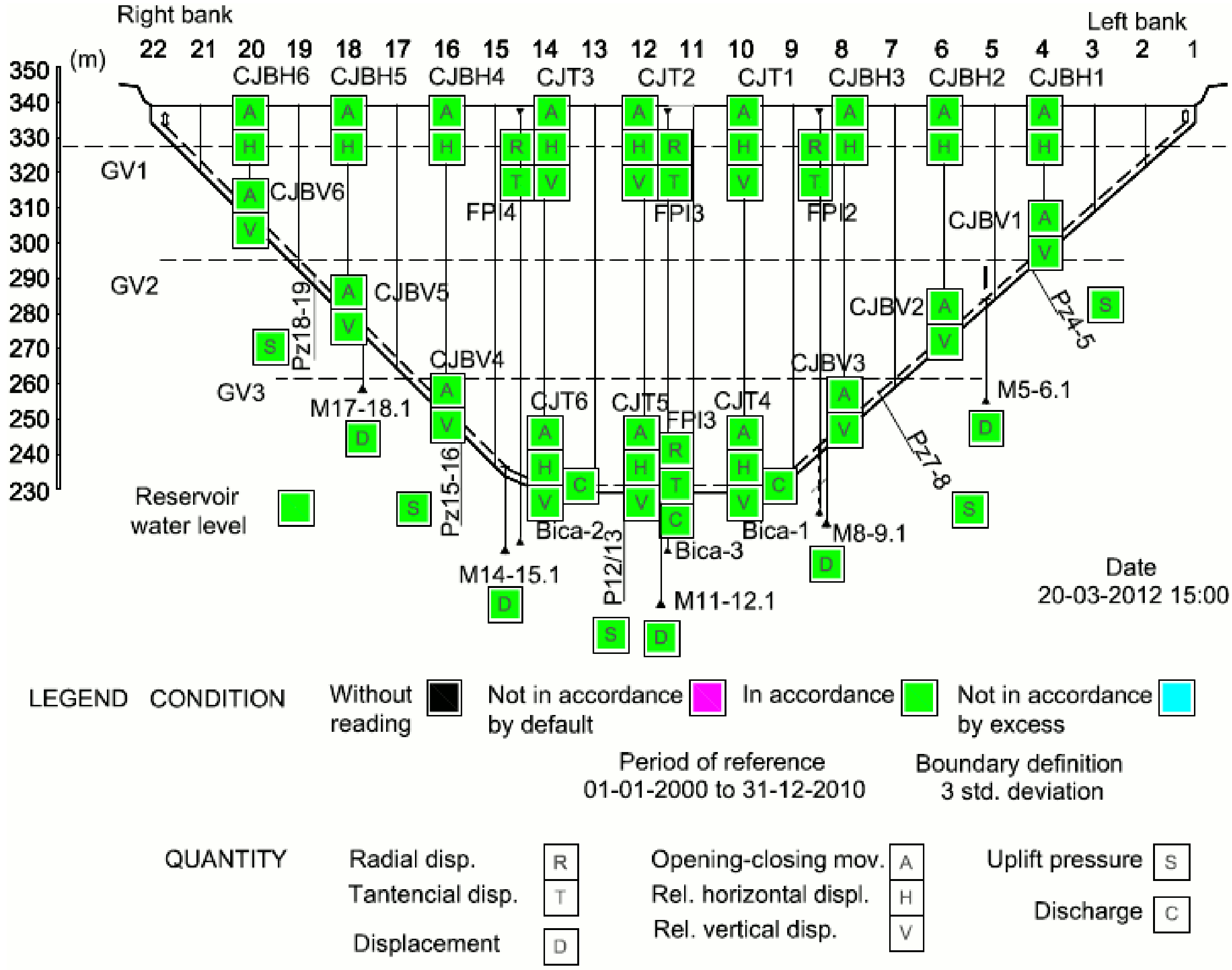

Figure 13 – Graphical example of a multiple quantity evaluation.

The main idea of the development of an application for the graphical representation suggested in Figure 13 is to classify the quantities based on previous thresholds. Taking into account the signal convention of the quantities, this representation may allow an overview of the dam and a timely identification of any potential accident scenario.

7 Final Remarks

The actual technological solutions allow the development of aid tools for the timely detection and reporting of anomalies in a scheduled form.

An IEWS can be considered as an integral part of the dam safety control process and a tool to aid in the identification of potential abnormal situations in real time.

An IEWS provides mechanisms for early detection of anomalies. It is possible to detect an abnormal situation and assign it to the appropriate technicians for the analysis. When it is integrated into other information systems, an analysis with the past dam behaviour can enhance the interpretation of the real situation, allowing the people responsible for dam safety to perform early and accurate responses.

The IEWS provides a basis for automated operations, so as to increase the measurement frequency when a threshold is exceeded, thus increasing the information to the person responsible for dam safety.

The IEWS should be robust and simple. This work presented a proposal for an IEWS that satisfies these requirements.

8 Acknowledgements

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9 References

DRAPER, N. R.; SMITH, H.. **Applied regression analysis**. John Wiley & Sons, Inc.; 1981.

EDP. **Design of Alto Lindoso Dam (in Portuguese)**, Porto, 1983.

FEDELE, R.; MAIER, G.; MILLER, B.. **Health assessment of concrete dams by overall inverse analyses and neural networks**. Int J Fract 2006;137(1):151–72.

ICOLD. **Methods of analysis for the prediction and the verification of dam behaviour**. Tech. Rep.; Swiss Committee on Dams; 2003.

JOGHATAIE, A.; DIZAJI, M. S.. **Nonlinear analysis of concrete gravity dams by neural networks**. In: Ao SI, Gelman L, Hukins DWL, Hunter A, Korsunsky AM, editors. World congress on engineering 2009. Lecture notes in engineering and computer science, vols. I and II. Hong Kong: Int. Assoc. Engineers, p. 1022–7; 2009.

MATA, J. **Interpretation of concrete dam behaviour with artificial neural network and multiple linear regression models**. Engineering Structures 2011;33(3):903–910. Doi: DOI: 10.1016/j.engstruct.2010.12.011 0141-0296.

MATA, J.; PORTELA, E.; DIAS, J.. **A neural network approach for seepage control of Alto Rabagão dam**. In: 75th Annual Meeting of the International Commission on Large Dams. Saint Petersburg: VNIIG; 2007, p. 12.

MONTGOMERY, D. C.; RUNGER, G. C. **Applied statistics and probability for engineers**. John Wiley & Sons, Inc.; 1994.

ROCHA, M.; SERAFIM, J.; SILVEIRA, A.. **A method of quantitative interpretation of the results obtained in the observation of the dams**. R.84, Q.21. In: VI ICOLD congress. vol. II., p. 927–60, New York. 1958.

PERNER, F.; KOEHLER, W.; OBERNHUBER, P.. **Interpretation of Schlegeis dam crest displacement**. In: Sixth benchmark workshop on numerical analysis of dams. International commission of large dams, p. 10., Salzburg. 2001.

PORTELA, E.; PINA, C.; SILVA, A. R.; GALHARDAS, H.; BARATEIRO, J.. **The modernization of information systems of dams: The GestBarragens system (in Portuguese)**. Seminário Barragens: Tecnologia, Segurança e Interacção com a Sociedade. Lisboa, Portugal. 2005.

SILVA, A. R.; GALHARDAS, H.; BARATEIRO, J.; MATOS, H.; GONÇALVES, J.; PORTELA, E.. **Data analysis features of the GestBarragens system**. International Conference on Innovate Views of .NET Technologies (IVNET06). Rio de Janeiro, Brazil. 2006.

SILVA, A. R.; GALHARDAS, H.; BARATEIRO, J.; PORTELA, E.. **The information system GestBarragens (in Portuguese)**. Seminário Barragens: Tecnologia, Segurança e Interacção com a Sociedade. Lisboa, Portugal. 2005.

YI, X. D.; XU, F.; JIANG, C. K.. **Research on dam deformation forecast model based on genetic algorithm neural network**. In: Wen TD, editor. ISTM/2009: 8th international symposium on test and measurement, vols. 1–6. Hong Kong: International Academic Publishers Ltd., p. 1536–9; 2009.