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Using neural networks in earthfill dams emergency planning

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Abstract

Safety control of dams is made during the normal exploitation phase, with the support of monitoring data from the observation system and also from the visual inspections information and data, by comparing the real and actual measurements with the values predicted by models of the expected dam behavior. The analysis of abnormal situations obliges to an intervention performed by a dam safety specialist who, facing the data from the observation system and the dam behavior model, will define the correspondent emergency level.

This traditional approach, used on a daily basis for assessing dam safety, is adequate, but sometimes, it may delay significantly the actions to restore dam safety standards. In fact, a important time period can occur, between the identification of an abnormal situation in the dam and the definition of the level of seriousness associated, as well as all the subsequent actions. The use of new technologies to help decision support and emergency planning can contribute to mitigate the effects of this disadvantage.

The current paper presents a case study concerned with the use of an artificial neural network (ANN) in order to evaluate the behavior of an earthfill dam, Valtorno-Mourão Dam in Portugal. The developed model allowed the identification of both normal and abnormal situations, establishing the correspondent dam alert levels.

keyword: Dams, neural network, observation system, emergency planning.

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1 Introduction

1.1 Emergency Management

In recent years, dam safety assessment and emergency management are becoming commonly assured by automated systems, with more or less human assistance. Therefore, automated data acquisition systems continuously monitor the dam, transferring information to a central dam safety and emergency operation center. In these centers the global behavior of the dam is evaluated and, if necessary notification messages to a pre-defined list of maintenance personnel and experts are issued, calling for correction measures and, when the emergency level obliges, warning the downstream population by an early warning system.

In this automated general system, it is very important of being capable of detecting the occurrence of an extreme event or of an anomalous structural dam behavior, and rapidly define its level of seriousness. According to most of the current practices, four emergency levels are usually defined, corresponding to a growing level of dam emergency. For each level, the set of situations defined for the dams is as follows (VISEU, 2006):

- Emergency level 0 – minor incidents occurring in the dam which do not compromise its structural safety (for instance, the occurrence of high intensity precipitation);
- Emergency level 1 – unusual event or anomalies slowly developing leading to possible discharges (effects in the downstream valley);
- Emergency level 2 – anomalies that may compromise the structural safety of the dam, rapidly developing; this situation may eventually lead to dam failure and to the occurrence of flash floods downstream;
- Emergency level 3 - dam failure appears imminent or is in progress and cannot be prevented; flash flooding will occur downstream of the dam.

1.2 Dam Safety Assessment

The knowledge of the dam behavior is usually supported by monitoring activities and relies on the comparison of the observed data, provided by the dam safety monitoring system, with the results of models that represent the dam structural and hydraulic behavior, thus requiring forethought expertise.

Deterministic and statistical methods have been used to develop models to predict dam behavior. The deterministic modeling requires solving differential equations for which closed form solutions may be difficult to obtain. On the other hand, statistical models rely on the adjustment of empirical expressions to monitoring data, deriving equations that make it possible to predict the dam's behaviour.

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This traditional approach, used on a daily basis for assessing dam safety, is adequate, but may delay significantly the actions to restore dam safety standards. In fact, a significant time period can occur, between the identification of an abnormal situation in the dam and the definition of the level of seriousness associated. One of the reasons is that the expert may not be immediately available when the situation occurs.

The use of new technologies to decision support and emergency planning, namely a "real-time" forecasting model of dam behavior, can contribute to mitigate the effects of this disadvantage. Important developments in the area of artificial intelligence were achieved in the recent years, trying to implement models that can perform an integrated analysis for all the monitoring data and, in accordance to rules pre-defined by behavior models and experts, can also perform alarms and recommendations concerning anomalous monitoring data (PORTELA (1999); MATA (2008); TAVARES (2011)).

2 Valtorno/Mourão Dam Case Study

2.1 General Characteristics of the Dam

The Valtorno-Mourão earth dam is located in the municipality of Vila Flor. Its main purpose is to supply water to Vila-Flor and other towns located nearby. The dam has a homogeneous profile with a maximum height of 32 m above the foundations, and includes an inclined filter and a drainage blanket to control the seepage (Figure 1). The fill material came from reclamations located in the local area of the reservoir is mainly constituted of soils resulting from schist decomposition.

Figure 1: Upstream and downstream view of Valtorno-Mourão dam (MARCELINO et al. (2010))

The crest of the dam is straight and has a length of 150 m and a width of 6 m. The downstream slope has 1(v):2(h) gradient and includes a bench at an elevation of 453 m. The upstream slope is less steep having with a gradient of 1(v):3.5(h).

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The foundations of the dam are constituted of schist and granite. The former occur in the right abutment, where they are very weathered. Schist also appears in the left abutment, upstream of the grout curtain. Granite appears downstream of the curtain in the left abutment.

Seepage control in the foundation is achieved by a grout curtain, formed after the cleaning of the foundation surface and the creation of a plinth.(MARCELINO (2005)).

2.2 Dam Behavior during the First Reservoir Filling

After an mandatory initial survey, the portuguese authority for dam safety (INAG) gave permission to initiate the reservoir's first filling. The first filling step was attained after 40 days, in October 2006, giving an average rise of the water level of 22 cm per day.

The displacement records at that time were quite normal. The maximum settlement was about 5 cm. This value was inside the expected range.

On the other hand, seepage flow recorded at the dam's toe was much higher than expected. According to the FEM model established in the monitoring plan, the total flow to the maximum water level (MWL), should be about 2.6 l/s. Instead, values recorded, in the 1st filling step, were up to 10 times this value. Figure 2 plots the reservoir's water level and the measured flows against the date. As can be seen from the figure, the flow rates recorded in December 2006 and January 2007 were higher than 20 l/s, but for the first filling step instead than at the MWL as forecasted by the model.

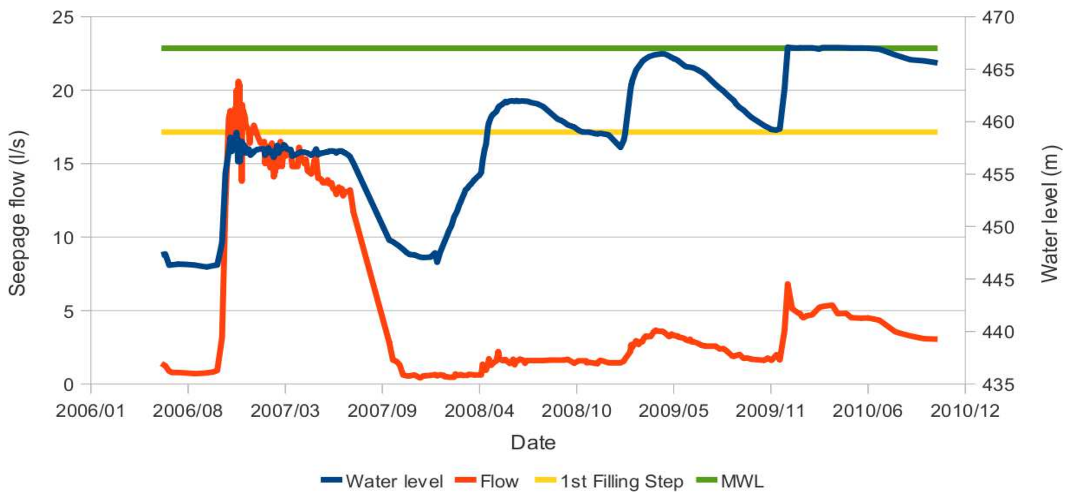

Figure 2: Water level and seepage flow against date (MARCELINO et al. (2008))

In addition to these issues, there were other symptoms of poorly functioning foundations. The standpipe piezometers located in the foundation, downstream of the grouting curtain, exhibited high water pressures, and the piezometers located above the drainage blanket also recorded pressure. These piezometers should never record pressure under normal conditions as the drainage blanket should contain all the seepage.

It was then decided to stop the first filling of the reservoir and proceed to the reinforcement of the foundation treatment. The works were carried out from September 2008 to February 2009, after which it stated again the (second) first filling of the reservoir, ie, the first filling was retaken. (Marcelino et al., 2010).

2.3 Dam Waterproofing Reinforcement

The waterproofing reinforcement consisted of the injection of grout via 29 holes from the crest, with an initial spacing of 3.0 m and inclined by 60º to the abutments, except for three holes in the central zone that due to the presence of the bottom discharge conduit were vertical. To avoid damaging the earthfills, filters and drains, the drilling of the embankments was made in dry conditions by continuous auger and using coating. In rock, the drilling was carried out by rotation with continuous recovery of samples and systematic Lugeon tests.

To protect the earthfill against water return circulation during drilling, it was decided that the coating tubes should penetrate about 0.50 m into the foundations on solid rock and the connection was to be sealed by cement grout.

The treatment by injection of the curtain in the dam’s foundations was carried out over 170 m of length, between the right and left abutments, with a height ranging between 15 m at the bottom of the valley and left abutment and 30 m on the right abutment. The total area of the curtain created by this treatment was 3200 m2, including the area under the spillway.

The injections were made by the successive approximations method. Initially the treatment consisted of injections via the primary and secondary holes provided for in the project and still some holes to the reinforcement of the abutments, where a lot of uncompressed solid rock with open joints was detected.

Given the difficulties in obtaining refusal and the high consumption of cement, resulting from the poor quality of the rock foundation, it was decided to continue treatment with a second phase of injections with tertiary and quaternary holes in the most critical zones, near contact with embankments and those identified by the geotechnical zoning.

After conclusion of the treatment, the filling of the reservoir re-started according the same plan that was initially established. As regards to seepage flow, the behaviour of the foundations was substantially different than that previously registered. It was verified that, although the total flow was slightly higher than predicted by the model, an acceptable behaviour of the foundations had been achieved.

3 Albatroz Neural Model

3.1 Introduction

The ANN model developed in this study (Albatroz model) is based on the structure of the multi-layer perceptron (MLP). It is a nonlinear input–output model and one of the most popular neural network types. The structure of the MLP consists of a network of neurons linked together by connection pathways. The neurons are arranged in a cascade of layers, each layer performing a function in the overall operation of the network (see Figure 3).

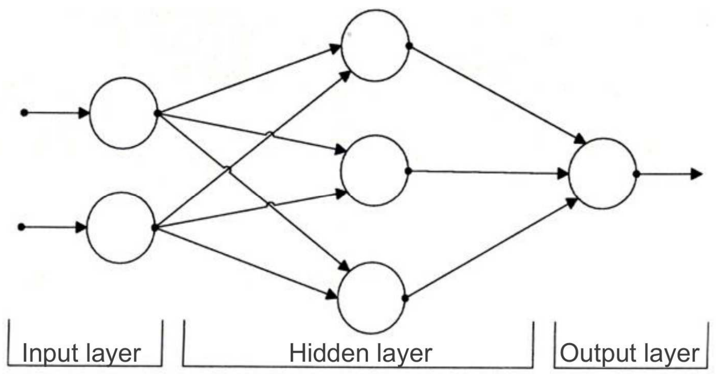

Figure 3: Schematic diagram of a MLP neural network (MATA (2007))

The simplest form of the MLP consists of three layers; input layer, hidden layer and output layer. Adjacent layers are connected by links governing the flow of information. The connection weights between adjacent layers are the parameters of the network which are to be estimated by training the network (learning procedure).

The first layer in the MLP receives the external input data to the network.

The hidden layer is an intermediate layer which enhances the capability of the network to deal robustly and efficiently with complex nonlinear modelling problems. The input–output transformation in the hidden layer is achieved by a mathematical nonlinear transfer function. Usually, the sigmoid function is used. This function has a S shape and its range varies between 0 and 1. As the actual external outputs of the network are generally outside the bounded range of the neuron transfer function, it is necessary to rescale or transform the actual (i.e. observed) external outputs to be within the bounded output range in order to make direct comparisons between the network estimated outputs and the external rescaled actual outputs.

The output layer is the last layer in the MLP; its main objective is to produce the final network results. The input–output transformation of the output neuron is similar to that of the hidden neurons.

3.2 General Characteristics of the Albatroz Model

In the present work, the ANN developed (Albatroz model) has the general characteristics presented in Figure 4.

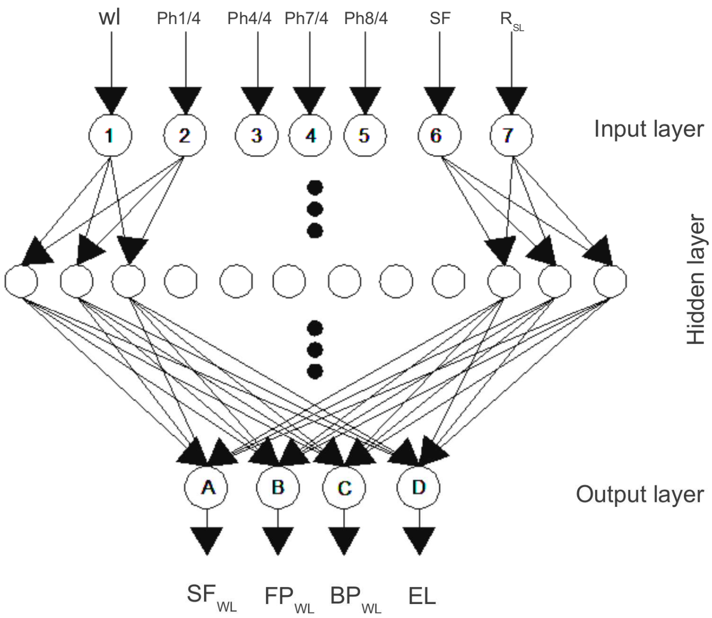

Figure 4: Schematic diagram of Albatroz neural network (TAVARES (2011))

The input layer is composed by seven neurons and corresponds to the following variables (see figure 5):

- Water level - wl - in the reservoir (neuron 1);
- Pore water pressure in the foundations measured in piezometers number PH1/4, PH4/4 and PH7/4 (neurons 2, 3 and 4);
- Pore water pressure in the downstream dam body (PH8/4, neuron 5);
- Total seepage flow (SL, neuron 6);
- Relative seepage flow (RSF, neuron 7).

The intermediate layer is composed by twenty neurons; this has been estimated by a trial-and-error procedure.

The output layer is composed by four neurons which are the diagnostic of the dam behaviour. As presented in Figure 4, the following output neurons have been defined:

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- assessment of the dam safety behavior level associated to seepage flow (SF_{WL}, neuron A);
- assessment of the of the dam safety behavior level associated to water pressure in the dam foundation (FP_{WL}, neuron B);
- assessment of the dam safety behavior level associated to the water pressure in the downstream dam body ($BP_{WL,}$ neuron C);
- assessment of the dam emergency level (EL, neuron D).

The diagnostic concerning the dam behavior is done by the values given for the first three output layer neurons, according to the expected values coming from the FEM Valtorno/Morão dam behaviour model established in the monitoring plan. The values of the first three neurons can assume values varying between 0 and 1. The zero value represent a classification of "normal" for seepage flow and water pressure in the dam foundation and downstream body while the value of one represents a classification of "inadequate behavior".

A different convention has been adopted for the last output neuron - assessment of the dam emergency level. Therefore the following criteria have been defined (see classification in section 1.1):

- values varying between 0 and 0.75 represent at the dam an Emergency Level 0 (minor incidents occurring that do not compromise the dam structural safety);
- values varying between 0.75 and 1.5 represent at the dam an Emergency level 1 (unusual event or anomalies slowly developing leading to possible discharges, i.e., effects in the downstream valley);
- values varying between 1.5 and 2.25 represent at the dam an Emergency level 2 (anomalies that may compromise the structural safety of the dam, rapidly developing; this situation may eventually lead to dam failure and to the occurrence of flash floods downstream);
- values varying between 2.25 and 3 represent at the dam an Emergency level 3 (dam failure appears imminent or is in progress and cannot be prevented; flash flooding will occur downstream of the dam).

3.3 Learning Process of the Albatroz Model

ALBATROZ Model is an ANN with the ability to predict the emergency levels of the Valtorno/Mourão dam. It used a supervised learning process based on a Error Back Propagation Neural Network algorithm. It is an iterative procedure that consists in the modification of the connection weights between adjacent layers in order to minimize differences (errors) between the expected and calculated outputs.

The learning procedure involves the use of examples (input data set jointly with the correspondent output sets) which allows the ANN to generate the problem representation.

Therefore, the first steps are the following:

- to collect input data from the monitoring dam system in the sensors chosen to define the diagnostic of the dam safety (water levels, pore water pressures and seepage flow);
- to assess the alert level associated to the measured values.

As the data set obtained by this process is short and does not to translate all the situations (normal and inadequate) that can occur in the dam, a second data set was artificially generated. For this generation, the FEM Valtorno/Morão dam behavior model was used. Based on the results and on the experience of dam safety and emergency experts, artificial data sets representing both normal and abnormal situations were prepared.

The sequential approach is as follows:

- to define the possible loads (normal and abnormal), i.e, hydrostatic pressure associated to reservoir water levels;
- to estimate the correspondent dam response (pore water charges and seepage flow in the chosen sensors), using a FEM model of the Valtorno/Morão dam;
- to assess the safety and emergency levels associated to the generated values, analyzing the dam response and defining the correspondent diagnostic of the dam behavior,i.e, to give output values according to the criteria presented in 3.2;
- to build input data sets of “reservoir loads - dam safety and emergency levels”.

A data set with 258 lines, representing possible combinations of situations corresponding to normal and inadequate behavior of the dam was generated. Each line has the input data and the correspondent output classification.

From the 258 sets, 220 were selected for the Neural Network training. The remaining 38 were used to test the accuracy of the predictions with respect to the results derived from the observation system and from the dam's numerical model.

The computer time necessary to complete the learning process can be very high and therefore the calculations were performed in the cluster “Medusa” (276 CPUs, RAM of 284 GB, disc of 6 TB and a HPL of 1,0 TFlops). “Medusa” is a cluster of 69 computers Fujitsu Primergy RX220 linked by Gigabit Ethernet connexions. During the training the model used just a small sub-set of the “Medusa” cluster.

The learning processing was considered finish when Albatroz model showed the ability of predicting Valtorno/Mourão dam safety and emergency levels, leading to very close

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predictions of the normal and abnormal situations of dam safety for all the 38 situations used to test its accuracy.

3.3 Application of Albatroz Model to Valtorno/Mourão Monitoring Data

After having accomplished the learning process, data from the monitoring system was used to estimate the dam emergency level. The available data concerns two different time periods (before and after the foundation reinforcement):

- the first one, which had leaded to the interruption of the first filling of the reservoir as a consequence of an inadequate dam behaviour, for which a data set with 76 situations was prepared;
- the second period, after the dam waterproofing reinforcement, for which a data set with 95 situations was prepared.

Albatroz model was tested in order to see the performance of the trained ANN in identifying the two pattern of dam emergency levels.

For the application phase, the input files have the values of the reservoir water level, seepage and pressure in the selected sensors. The result files give the assessment of the safety level associated to seepage flow, to water pressure in the dam and in the downstream dam body as well as the dam emergency level.

The results obtained for both periods are summarized in Figure 5.

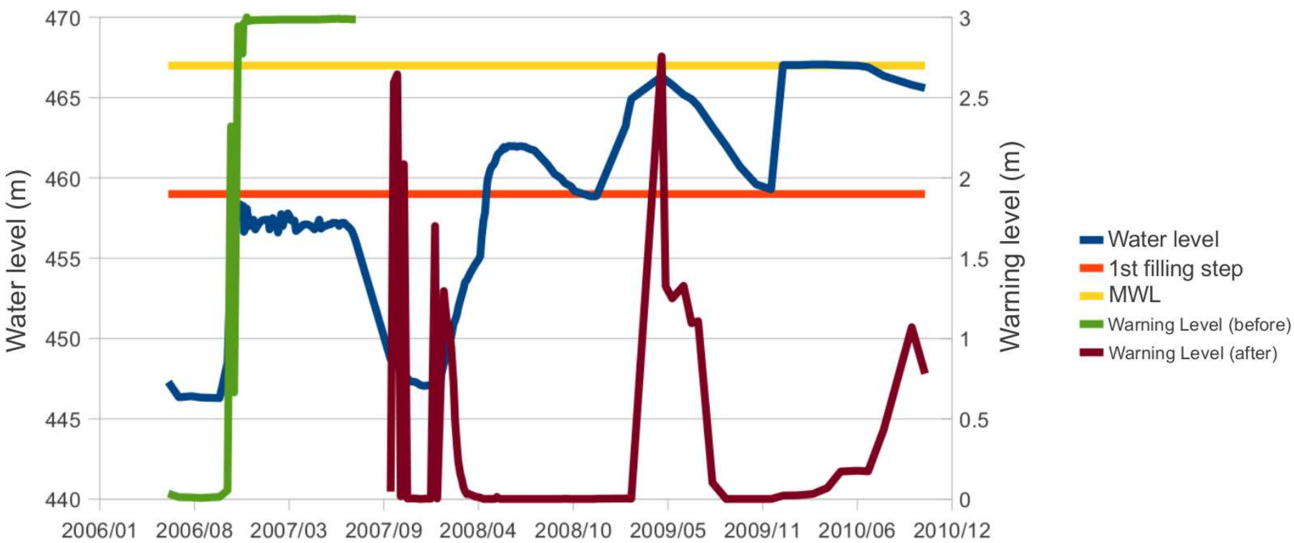

Figure 5: – Dam Alert Level identified by ALBATTROZ model, before and after reinforcement (TAVARES (2011))

It can be observed the safety situation of Valtorno/Mourão dam before reinforcement was well identified by the model. In fact, the higher level of emergency (3) was predicted 89,6% of the 76 situations envisaged.

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From this figure, it also can be observed that the Albatroz model identify the period after reinforcement, as the minor levels of emergency (0) and (1) were respectively identified for 81% and 13.7% of the 95 situations occurring in the dam, after reinforcement.

4 Conclusions

This paper presents an example of application of a model using a multilayer perceptron neural network to the monitoring results of an embankment dam in order to identify anomalies and establish dam emergency levels.
A Back Propagation Neural Network algorithm was applied to produce estimates of the emergency levels, regardless the complexity of the problem, leading to very close predictions of the normal and abnormal situations of safety lived in Valtorno-Mourão Dam before and after the dam waterproofing reinforcement .
One of the major advantages of a ANN model is that it is readily available regardless of the complexity of the dam. ANN models can incorporate subjective knowledge and experience from dam experts in a very straightforward way.
Although ANN models do not avoid the need of human intervention and judgment, they are strong tools that can help dam safety control.

5 Acknowledgements

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