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ESTABLISHMENT OF VALUES OF CONTROL FOR INSTRUMENTATION AND AUTOMATIC ALERT SYSTEMS FOR EMBORCAÇÃO DAM *

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1. INTRODUCTION

Emborcação is a 158 m high earthcore rockfill dam, located on the Paranaíba River, holding a reservoir of 17.5 x 10^9 m^3 of water and having a 1192MW powerhouse. Its construction was carried out in the period 1977-1981 and it is operated by Cemig Geração e Transmissão S.A.

The rockfill dam has an upstream inclined core and an internal impervious blanket. The inclined core was adopted to avoid hangup of the clay core under the predicted differential settlements between it and the rockfill. The internal impervious blanket was built to extend the percolation path, minimize the use of rockfill and reduce differential settlements, since it was made up of materials with deformation characteristics similar to the core [1]. Despite the efforts made during the project, the deformations of the dam were higher than predicted, with settlements reaching 3.8 m during the construction period and the first filling of the reservoir, and with longitudinal cracking of the crest appearing at the downstream edge of the core.

* *Établissement de valeurs de contrôle pour les appareils de mesure et d'alarme au barrage de Emborcacao*

Fig. 1
Emborcação Dam
Barrage d'Emborcação

Emborcação dam is instrumented as presented in Table 1, showing the operating conditions of the instruments after 26 years of operation.

Table 1
Instrumentation installed at Emborcação Dam

	Installed	**Disabled**	**Damaged**	**In operation**	**% in operation**
Surface monument	70	16	2	52	74%
Weir	5	0	0	5	100%
Pneumatic settlement sensor (Hall)	23	23	0	0	0%
Water level settlement gage (Swedish Box)	30	14	16	0	0%
Pneumatic piezometer (Hall)	29	3	3	23	79%
Electric piezometer (Maihak)	2	2	0	0	0%
Total Pressure Cell	17	1	3	13	76%
Inclinometer (Settlement)	5	3	0	2	40%
Inclinometer (Deflexion)	5	4	0	1	20%

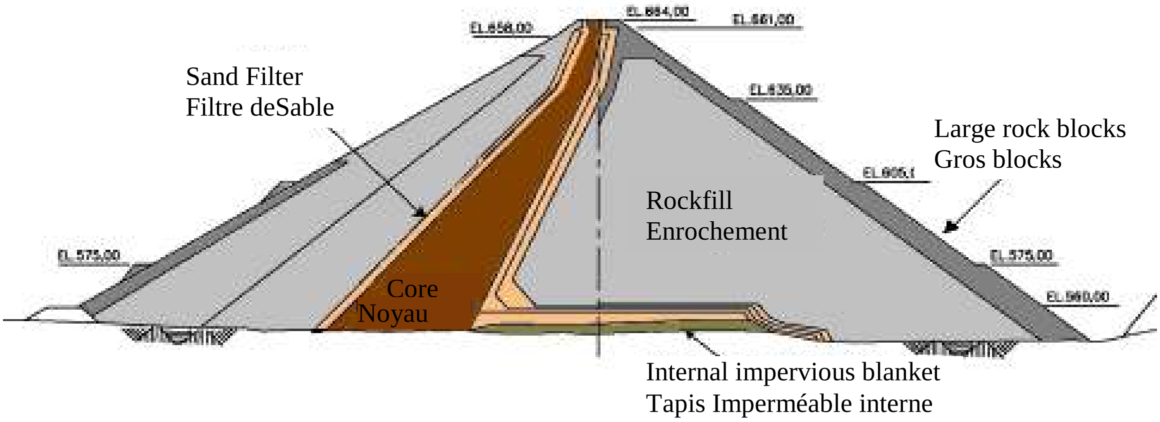


Fig. 2
Emborcação dam – Typical cross-section
Barrage d'Emborcação – Section transversale type

Now, after 26 years of operation, the rate of deformation has reduced significantly, but the focus on the control of displacements, porepressures and total pressures (tensions) in the core continues. All instruments in operation are read, and the information collected is sent to a data basis, to allow reduction, check of errors, edition of information and plotting.

However, in order to obtain the maximum benefits from instrumentation, detailed evaluation and interpretation of the results should be made immediately after the collection of the data. The most common and less justifiable deficiency of the current evaluation programs of the behavior of dams in Brazil is probably that originating from of the fact that the data stay without interpretation until one's analysis becomes late or obsolete for the acquisition of new readings.

The instrumentation data management systems in Brazil include, basically, readings' storage, the calculation of the respective measures and their plotting to systematize the results. Many of these systems consider deterministic reference values established by the dam designers, which, if exceeded, would constitute an automatic alert in the sense that the factors of safety of the dam would be below the ones set up during the design. Few dam owners have more consistent automatic alert systems that recognize changes in the historical pattern of readings able to indicate an unusual behavior of the structures.

The present paper aims to approach and discuss the application of deterministic and statistical methods as tools in the preliminary analyses of the instrumentation data of Emborcação dam and in the establishment of alert flow charts that could indicate changes in the behavior of the structures of the dam.

2. DETERMINISTIC FORECASTING MODELS FOR MONITORING EMBORCAÇÃO DAM

2.1. CONCEPTS OF DETERMINISTIC MODELS

Deterministic models used for evaluating instrumentation data consist of models of structural analysis, calibrated using the measurements of the physical variables under analysis taken from the field instrumentation. The results of these analyses are mathematical cause-effect relationships.

The data reports of the instrumentation installed during the construction or even during the life of the dam are useful in the deterministic studies, because they are used in the calibration of the model. This calibration is accomplished through successive simulations of the flow conditions, until reaching the condition that best reproduces the phreatic line observed in the field. Different ratios of vertical and horizontal permeability (kv/kh) are tested for the dam and its foundation and one may need to reevaluate other important geotechnical parameters in the studied model. The porepressures, levels of water and displacements obtained numerically are confronted with the values registered by the field instruments, until getting the appropriate adjustment.

In the case of the deterministic models, the reliable behavior of the dam is indicated by the agreement between the measurement in the field, which would characterize the behavior of the dam, and the value foreseen analytically for the corresponding loading conditions. Usually, the values obtained through the numeric model are considered ‘limits' for the evaluated variables, in other words, field measurements superior to the values established by the model would indicate a factor of safety below the one established in the project of the dam.

The use of deterministic methods in the establishment of reference values (or values of control) for instrumentation readings has restrictions, due to the following factors:

- in the case of earth or rockfill dams, the obtained limits indicate basically the possibility of rupture by slope failure, disregarding other failure modes such as piping or excessive settlement of foundation;
- the values obtained for each instrument are usually fixed and unable to show changes in the measurements according to the variation of the loading conditions;
- the analyses usually don't consider the variability of the geotechnical parameters;
- there are many causes of differences between the values foreseen in project and those obtained by the instrumentation, and a mathematical model, no matter how detailed it was and how discerning its calibration

was, will never be able to represent with perfection all the characteristics of the dam and its foundations and those of the installed instruments.

Despite these restrictions, the mathematical models are extremely important in the evaluation of the safety of a structure and in the control of its performance along the time, because they put in evidence the conception, the premises and the designer's objectives during the project.

2.2. PREDICTING INSTRUMENTATION READINGS AT EMBORCAÇÃO DAM USING DETERMINISTIC MODELS

The project of Emborcação dam began in 1976, period in which many large rockfill dams were being designed in Brazil, such as Foz do Areia (a 160m high rockfill with concrete face dam, the largest of this type at that time), Itaipu, Salto do Santiago and Tucuruí. The project of such dams put in evidence the need of estimating the deformations that would occur in the dam during and after construction and the period of the project coincided with an euphoria phase around the application of the Finite Elements Method in the forecast of deformations in dams.

At the project of Emborcação, the program used was ISBILD, developed by Ducan and Osawa (1973) in the University of California. The model used was the hyperbolic elastic one, with the parameters of deformability of the core obtained through triaxial tests and the one of the granular materials established from the technical literature, always considering the material of the core more compressive than the rockfill. However, during the construction, it was verified that the results were inadequate, considering the measured settlement of 3.9m, very superior to the foreseen value of 2.3m. In addition, longitudinal cracking appeared at the downstream edge of the core and on the upstream transition interface with the core. The conclusion was that the model considered had not been realistic and that the parameters adopted for deformability diverged from the real values verified in the field.

In relation to the prediction of porepressures, the models used at that time didn’t show satisfactory results and the flow net was obtained through the construction of a physical model executed by Leme Engenharia.

In the 1990’s, Carvalho [2] studied the seepage in the core of the dam, trying to calibrate the model with the tensions and porepressures measured in the dam, adopting a variety of parameters for the construction materials and admitting different horizontal and vertical permeabilities ratios. Satisfactory comparisons between numerical results and instrumentation measurements were obtained when permeabilities varied with the level of vertical tension (permeability decreasing with the depth) and for the condition of larger horizontal than vertical permeability in a growing ratio with depth (ratio between horizontal and vertical permeability increasing with depth).

Finally, a new analysis was carried out in 2005 by DAM Projetos, using the software developed by GeoSlope International Ltd.

The analysis main challenge continued to be the calibration of the deterministic model, adjusting the deformations of the model with the ones measured in field. The geotechnical parameters adopted were obtained through the laboratory tests during the construction period and new tests executed for this specific study, although persisting the need to use some parameters estimated in the project.

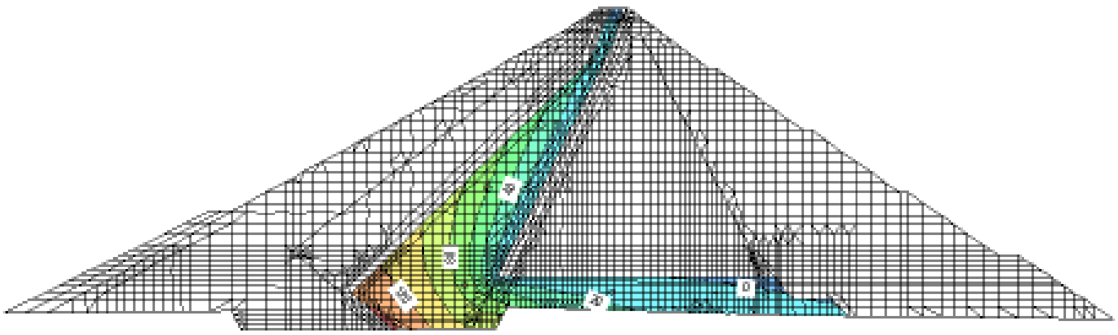


Fig. 3

Finite elements net for Emborcação dam

Maille des éléments finis pour le barrage d'Emborcação

Despite the effort to calibrate the model, deformations and piezometric loads obtained numerically showed significant discrepancy when compared to instrumentation measurements. In most transversal sections of the dam, only part of the instruments readings was in accordance with the numbers foreseen in the model, and for deformation, the discrepancy was even higher.

The attempts made until now demonstrate that, to develop a numeric model capable to represent a dam and the data of the field instrumentation appropriately, is not a simple task and it demands professionals with wide experience and knowledge. The author emphasizes the importance and the validity of the deterministic models, mainly in the phase of the first filling of the reservoir and in the first years of operation, when a time series of instrumentation observations is not available to allow the analysis of historical tendencies or correlation with other physical variables, and this models are the only source of information about the conditions of safety of the dam.

3. STATISTICAL FORECASTING MODELS FOR MONITORING EMBORCAÇÃO DAM

3.1. CONCEPTS OF STATISTICAL MODELS

The statistical models of stability analysis of earth dams are those that use statistical tools and probabilistic methods to incorporate the variabilities of the geotechnical parameters in the models of analyses. In this case, besides the safety factors, their respective probabilities of occurrence are calculated.

These models are of special interest in the safety of dams where there are many sources of variability of the geotechnical parameters, as, for instance, in the case of tailings dams built using hydraulic fill technique [3]. In earth and rockfill dams, these models aren't usually used, although the available softwares allow the consideration of the variability of several geotechnical parameters.

As described for the deterministic models, the analysis of instrumentation data can also be made using statistical models of stability analysis. However, due to the uncertainty sources, to the variability of the geotechnical parameters and the variability factors in the reading of instruments, the model would continue being imperfect and the readings of the field instrumentation even though could present divergences in relation to the foreseen values.

For this reason, this methodology is not usually applied in the analyses of the instrumentation of dams. Statistical models have been used for this purpose, consisting basically of time series analysis and the application of regressive techniques [4]. They intend to manage and analyze chronological measurements and can be used whenever a past report of readings exists. When, from the analysis of the statistical parameters obtained, the model is considered valid, it can be used in the confrontation with real measurements and in the forecast of future ones.

Menga et al. [5] mention several statistical methods used with the purpose of preliminary analyses of instrumentation data:

- scatter plots;
- simple or multiple linear regression;
- polynomial models;
- Fourier trigonometric polynomial models;
- time series;
- moving averages;
- maximum-minimum models in pre-established intervals.

3.2. PREDICTING PRESSURES AT EMBORCAÇÃO DAM USING STATISTICAL MODELS

Up to now, the studies and deterministic models developed for Emborcação dam couldn't establish, with the required precision, reference values for expected deformations and pressures. However, it is essential that these values are defined, to allow the automatic preliminary analysis of the data, incorporating higher quickness in the analysis of the instrumentation data and the early detection of problems in the dam. This was the reason for the search of expected values for the instrumentation of the dam using statistical methods.

The statistical studies were executed using regression methods, considering the instrumentation data after the impoundment of the reservoir. All statistical analyses were made using SAS (Statistical Analysis System).

Initially, a preliminary analysis of piezometer data was executed, plotting the series of pressures versus time to verify and eliminate the presence of anomalous values, which could be indicative of mistakes in reading or other inconsistent readings that should be excluded, not to generate distortions in the statistical models.

The second phase of the data analysis consisted of the search of explanatory variables for the linear regression, using Person's correlation test with a significance level of 95%. The reservoir level, downstream level and the difference between these two water levels were studied as possible explanatory variables.

It was verified that only few piezometers presented satisfactory correlation with one of these water levels (Figure 4), and all of them, except the instrument EMBTPH207(pneumatic piezometer), were installed in the foundation. This result was already expected, considering that a piezometer installed in a compacted embankment doesn't usually present an immediate answer to the changes in the reservoir level, which can be explained by the instrument response time and, mainly, by the time of seepage through the embankment.

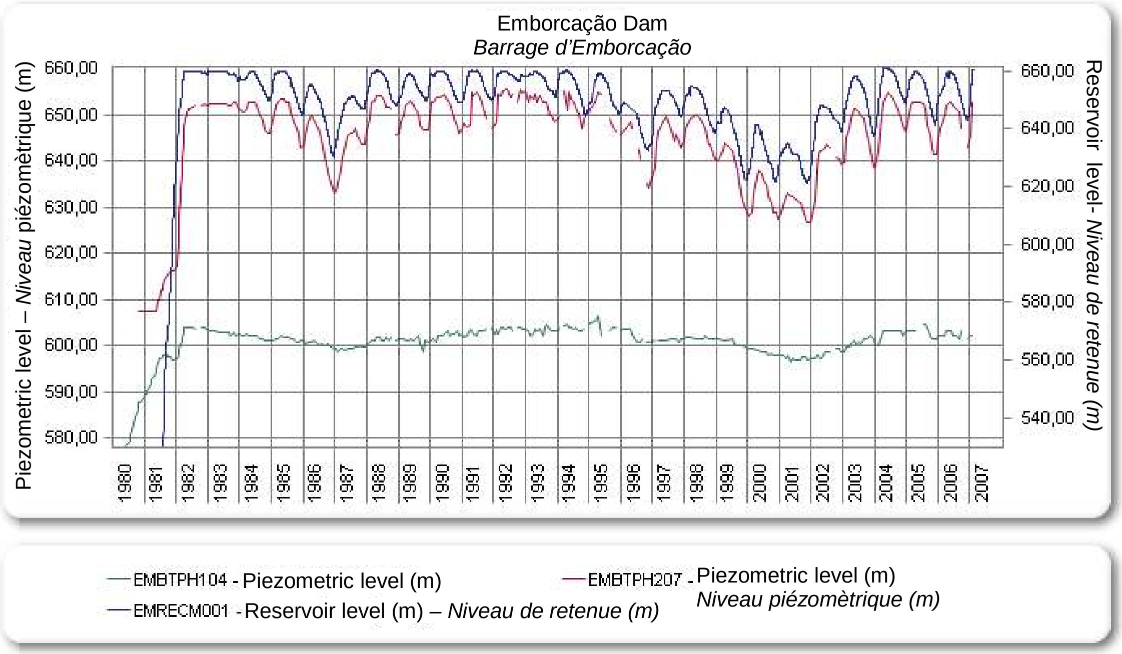


Fig. 4

Piezometers EMBTPH 207 and 104 time series, showing difference in the responses to the variations of the reservoir level

Séries temporelles de piézomètres EMBTPH 207 and 104, montrant la différence des réponses aux variations de niveau du réservoir

The usual solution for this type of problem has been to look for the ideal time-lag that allows significant correlation between the measured pressures and the water level in the reservoir or downstream; in other words, to determine the delay that should be considered between each water level and the respective reading of an piezometer or total pressure cell.

However, a previous and detailed reading of the data showed that most piezometers also didn't answer directly to a 'delayed' value of the reservoir level, but seemed to answer in agreement with a medium value of this variable; in other words, pressures seemed to have a relationship with a smoothed series of reservoir water levels. This was more visible for the instruments installed in the downstream side of the core.

Considering this observation, moving averages method (MA) was used to smooth out short-term fluctuations of the reservoir level, thus highlighting longer term trends or cycles. To test the correlation, the new observation of smoothed series was used in the date of the instrument reading.

As an example, Figure 5 presents the time series of the reservoir levels of and the same series smoothed using moving average MA 400. It can be seen that there is a better correlation between piezometric levels measured by pneumatic piezometer EMBTPH104 and the smoothed time series.

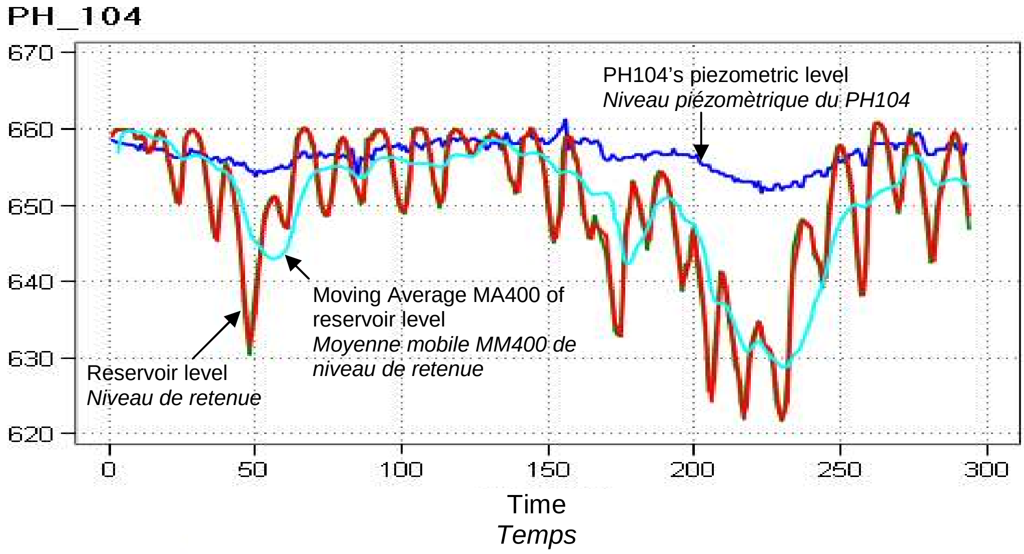


Fig. 5
Comparison between piezometric levels of EMBTPH104 and the smoothed time series of reservoir levels.
Comparaison entre les niveau piézomètriques du EMBTPH104 et la série temporelle du réservoir après le lissage de valeurs

However, for some piezometers and all total pressure cells, satisfactory correlations couldn't be obtained using the described method. A more detailed visual analysis of these series of readings showed a change in the pattern of behavior after 2003. Such change could not be explained by alterations in the measurement device, in the reading method or even in the behavior of the dam. To allow the analysis of these instruments, correlations were established for the period after the stabilization of the readings in the new pattern, considering this period representative of an acceptable behavior for the dam.

After obtaining appropriate correlation parameters for all instruments, scatter plots were used to check the behavior of each one and to put in evidence differing values that could be reading mistakes. The anomalous data were removed and, to justify this elimination of measurements, the regression analysis was made before and after the exclusion, comparing the results. This exclusion was justified when were verified a decrease of MSE (Mean Squared Error), an increase of R-square (percentage of variability of the data explained by the model) and a better adjustment of the residues, that, in some cases, started to assume a normal distribution.

As an example, the model developed for pneumatic piezometer EMBTPT106, after exclusion of the outliers, definition of the best correlation with the moving average of the reservoir level (in this case MA 30), analysis of the residues and the analysis of the variance.

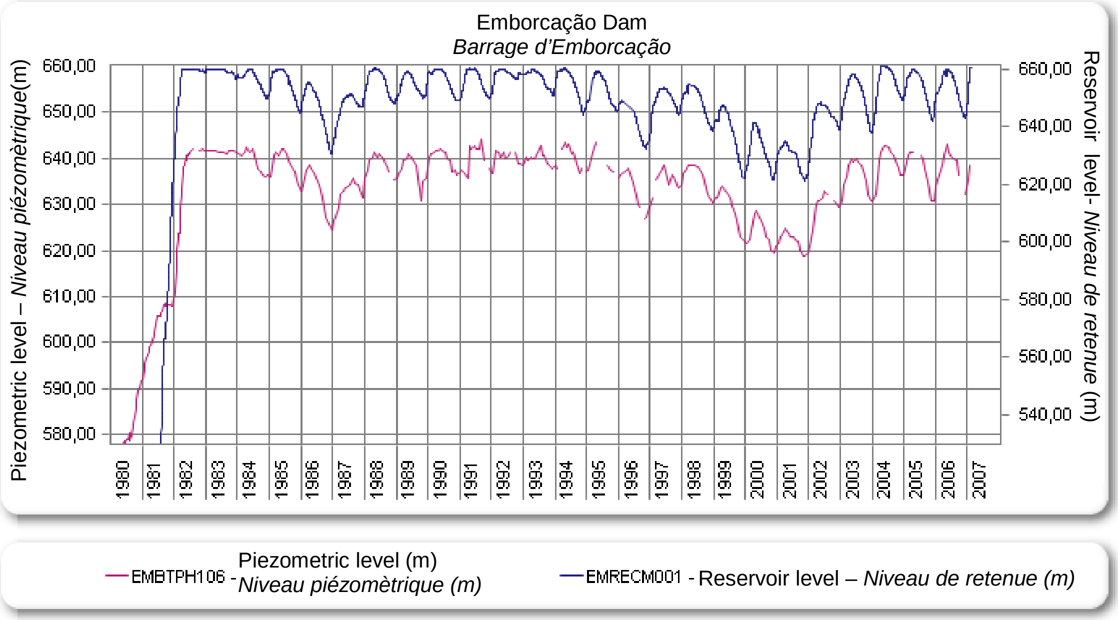
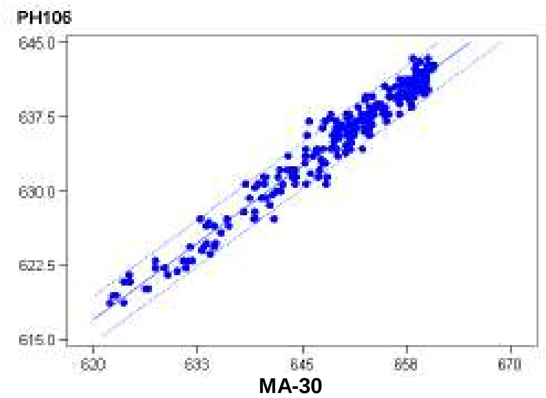


Fig. 6
Piezometric levels of EMBTPH106 and reservoir elevation
Niveau piézomètrique du EMBTPH106 et niveau du réservoir



PH106 = 232,709755 + 0,619844 * MA_30
R-Square = 0,96

Fig. 7
Linear regression for EMBTPH106, after the exclusion of outliers.
Régression linéaire pour le EMBTPH106, après l'exclusion des points incohérents

4. ESTABLISHMENT OF VALUES OF CONTROL AND AUTOMATIC ALERT SYSTEMS

According to the ICOLD [5], since the 1980's there has been a growing interest of the technical community in the establishment of reference values for the instrumentation data of dams. Nevertheless, after almost 30 years since the first attempts to establish these 'limits', their importance is still not recognized by most dam owners and operators in Brazil.

The expressions ’alert limits' and ‘emergency limits’ were disseminated in Brazil as the maximum values predicted in the project that could be reached by the measurement of an instrument and that would define alert situations. Other expressions such as ’values of control’, ' reference values’ or 'performance indicators’ are also used. The authors consider the last ones more appropriate because these ‘limits’ show the beginning of a trend that escapes from the established pattern of measurements throughout the years, but don’t necessarily indicate the possibility of failure of the dam.

The Corps of Engineers [6] affirms that “the anticipated range of each monitored parameter associated with satisfactory performance should be identified so that unsatisfactory performance can be identified. Threshold levels associated with the onset of unsatisfactory performance must be identified for each monitoring device. It is generally prudent to establish an alarm setting at a level between the range of satisfactory normal performance and the threshold level that will call attention to performance data that exceed historical data trends.”

A reliable instrumentation system should be capable not only of data processing, reduction and plots, but also to proceed the management of the anomalies, particularly in relation to the readings out of the acceptable ranges, by the immediate characterization of the corresponding alert. It must provide comparisons between actual and predicted behavior, means to detect data acquisition errors, determine trends or cyclic effects, compare behavior with other instruments, predict future behavior, and to determine instrumentation maintenance requirement needs. This allows the automatism of part of the evaluation accomplished by the technicians involved in these activities, generating alarms for situations of interest that should be analyzed in depth and guiding, in a dynamic and continuous way, the coordination work and supervision of the procedures of global control of the analyzed data.

With the real problems in the performance of the dam, a certain number of false alarms can occur. Therefore, it is recommended that the alarms emitted by automatic systems constitute essentially technical alarms, in other words, just intended for the agents of control of the dam.

4.2. VALUES OF CONTROL AND AUTOMATIC ALERT SYSTEMS FOR PRESSURES AT EMBORCAÇÃO DAM

In the establishment of values of control for porepressures and total pressures at Emborcação dam, a linear regression model was used. Although it’s a simple tool, it could represent most pressure time series adequately.

The **design limits** should be defined as values that represent the limit for acceptable pressure, which together constitute the performance criteria for a dam. They are established originally during design and generated by deterministic models, historical cases and judgment of engineering. In the case of Emborcação, the values predicted during the design period couldn't be used, because they differed completely from the instrumentation measurements. The values adopted were the ones obtained in the studies carried out in 2005, using up-to-date mathematical models.

The **consistency limits** were defined as those determined statistically and that predict future trends and expected values for a monitored parameter, considering its historical data. Generally, they can be graphically represented as a load-response relationship. In the case of Emborcação dam, they were defined from the correlation plot between piezometric levels or total pressures and reservoir elevation, defining the following zones of behavior (Figure 8):

- **Consistency zone**: the measurements are within the limits established statistically and below the design limit. If the measurement is inside this zone, the reading is considered correct and doesn't need additional immediate analysis;
- **Inconsistency zone**: the measurements are not within the boundaries established by the consistence limits, but below the design limit. It means that the reading does not follow its historical pattern. In this case, the reading should be investigated regarding its correction, the operation of the instrument should be verified and the causes of the anomalous behavior must be evaluated.

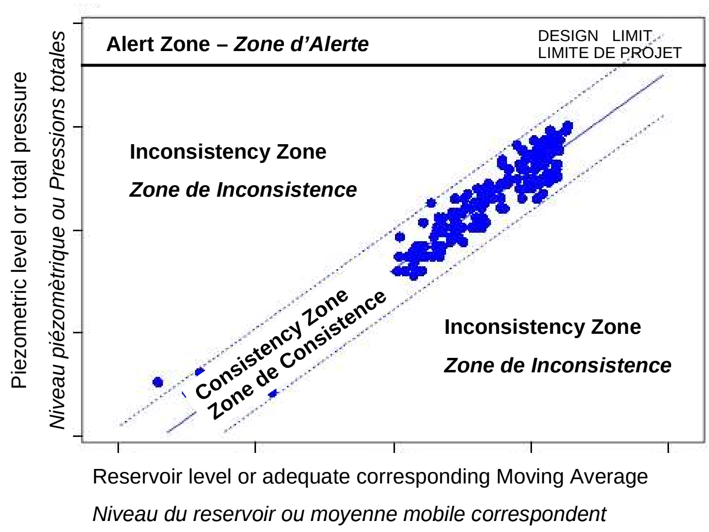


Fig. 8
Zones of behavior for Emborcação dam instrumentation
Zones de Comportment pour l'instrumentation du barrage d'Emborcação

Considering this values of control, a system of alert was established to indicate abnormal situations that should be evaluated by the dam safety team:

- **Design alert**: the measurements are above the design limit established. In this case, although a situation of imminent rupture is not configured, detailed evaluation of the conditions of the dam may be necessary;
- **Total pressure alert**: the total pressures are inferior to the value of control established, taking into consideration the correlation between total pressures and porepressures in a certain point of the embankment.
- **Consistency alert**: one measurement of a given instrument is not within the boundaries set up by the consistency limits;
- **Persistency alert**: two or more consecutive measurements of a given instrument are out of the consistence zone, with the readings increasing or decreasing with time;
- **Section alert**: several instruments at the same section or pre-established area present values out of the consistence zone;
- **State of alert**: several instruments at the same section or pre-established area present values out of the consistence zone, at least one of them for two consecutive readings. This can indicate a potential problem in the behavior of the dam and the causes of the anomalous values should be investigated immediately and with the necessary depth.

The characterization of automatic alert in the preliminary analysis of porepressure and total pressure data can be made as proposed in the flow chart of Figure 9.

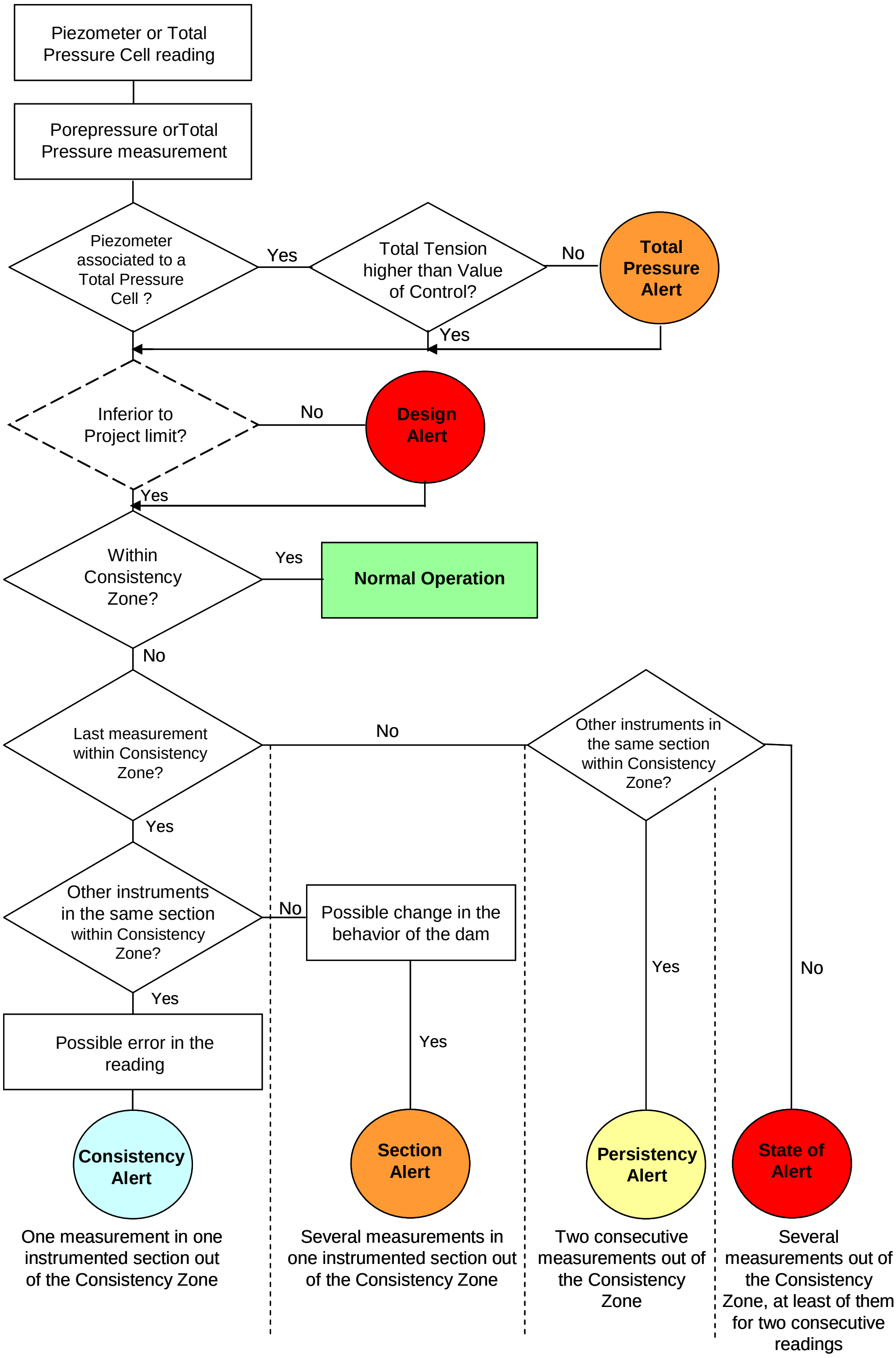


Fig. 9

Flow chart for an automatic alert system for pressure measurements at Emborcação Dam

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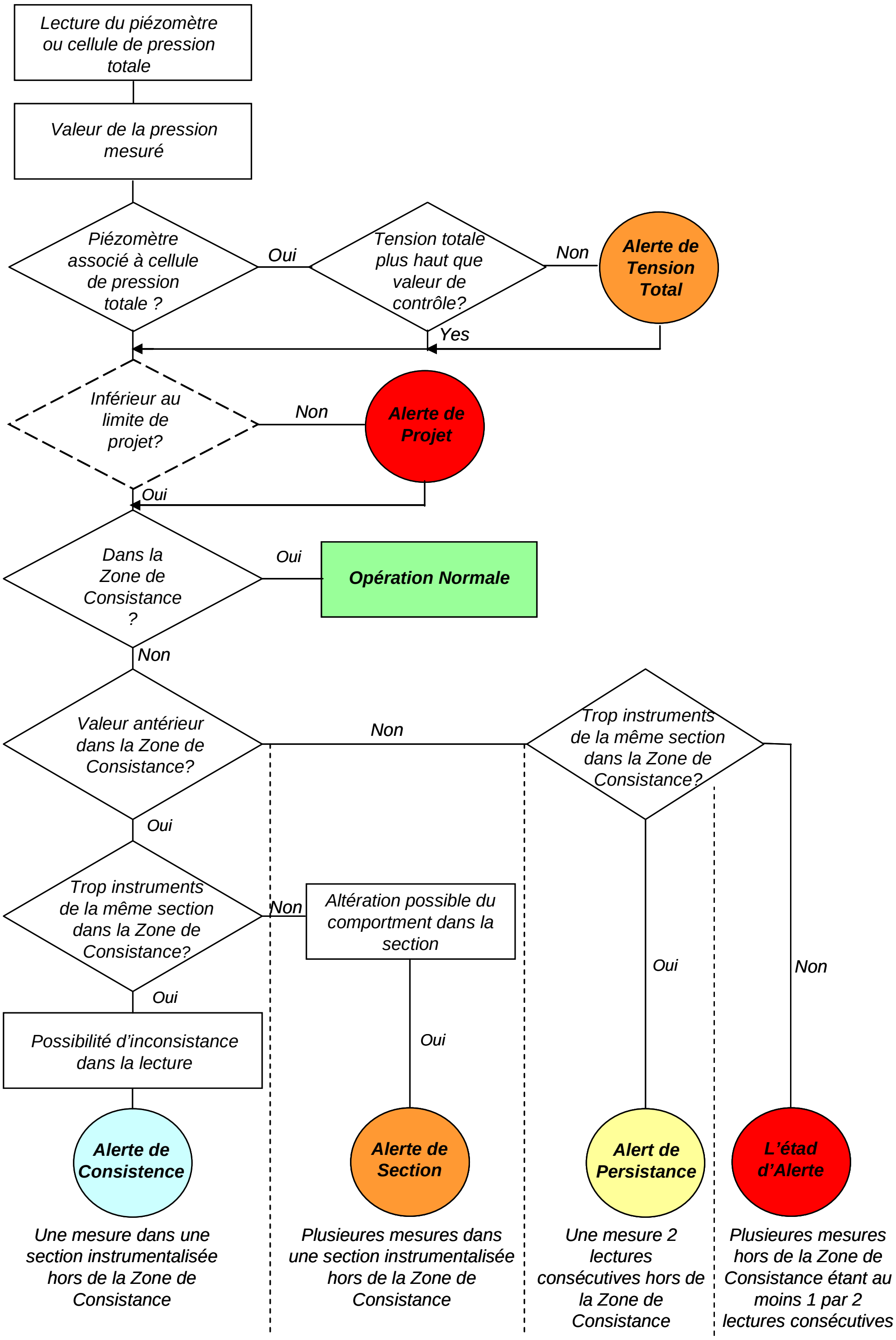

Fig. 9

Fluxogramme por um système d'alerte automatique pour mesures de pression dans le barrage d'Emborcação

CONCLUSIONS

The physical variables measured in a dam constitute time series that can be analyzed applying statistical methods, besides the deterministic ones already used in the design. It is important to determine statistical values of control for measurements in a dam, to allow the elaboration of automatic alert flow charts for situations diverging from the reference conditions historically detected by instrumentation.

The results of deterministic and statistical studies can be used to allow immediate characterization of signs of alert, corresponding to the situations of interest that should be analyzed in depth, and guiding, in a dynamic and continuous way, the work of the professionals involved in these activities.

Nevertheless, this doesn't eliminate the need of well trained engineers to analyze instrumentation information. The safety analysis of a dam involves the correlation of the measured values with the applied loads, determination of tendencies and careful comparison with the values theoretically or experimentally foreseen. It demands, therefore, experienced professionals and with knowledge on the general objective of instrumentation certain type of dam, of the tolerances and limitations of each instrument type and of the expected behavior of the analyzed structures.

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SUMMARY

This paper shows the application of deterministic and statistical methods as tools in the preliminary analysis of the instrumentation data from Emborcação dam, allowing automation of this process. It proposes an alert flow chart that aims to support the dam safety teams and contributes to increasing the speed in the analyses, so that the monitoring procedures are less empirical and more effective in the systematic verification of the geotechnical behavior of dams in operation.

RÉSUMÉ

Cet article montre l’application des méthodes déterministes et statistiques comme outils dans l'analyse préliminaire des mesures de l'instrumentation de barrage d’Emborcação, pour permettre l'automatisation de ce processus. Il propose un fluxogramme d’alerte, qui vise à soutenir les équipes de sécurité de barrages et contribue à augmenter la vitesse dans les analyses, de sorte que les procédures de surveillance soient moins empiriques et plus efficaces dans la vérification systématique du comportement géotechnique de barrages en opération.