

MULTIVARIATE ANALYSIS APPLIED TO CONCRETE DAM MONITORING DATA

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Abstract. *This work is focused on the monitoring of the responses of the concrete structures of the buttresses blocks of Sector D of the Itaipu dam, through the analysis of monitoring structural data and foundations of two blocks of the dam. Factor analysis was used to study the relationships between structure responses and block foundations, captured by the different instruments installed in it. The application of factor analysis intended to identify the sources of variability in data and the ordering of the sensors according to the action of factors. Then, using these results as input data, the Joint Monitoring Index Blocks Responses (JMIBR) of dam, was created in order to contribute to the diagnosis of changes in the dam's structural behavior pattern. The values obtained for JMIBR indicated that the monitored process was under*

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control, stable and, thus, the dam responses were predictable. Updated data were used for method validation.

Keywords: *Joint Monitoring Index, Displacements, Environmental Conditions, Factor Analysis*

INTRODUCTION

Dams are containment structures, constructed transversally to a river or valley for the purpose of obtaining elevation of its water level and/or creating a reservoir of water accumulation is to regulate the flow of the river, or of another fluid (MSIB, 2002, p.15).

Usually, dams are large structures that respond to internal processes arising from their constructive nature and influenced by environmental conditions in their surroundings. Therefore, according to NBR 8681 (2003, p.15), the safety of its structures must be checked in relation to all possible states that are admitted as limit, with respect to the analytical and constructive conditions.

In addition, the structural monitoring of dams aims to maintain their structural and operational integrity and the preservation of life, health, property and the environment (BRASIL, 2010, p.1).

This monitoring involves the measurement, through the auscultation, of the occurrence of displacements, deformations, tensions, pressures, among other phenomena that affect the structures and foundations of the dam. The instrumentation used for this purpose consists of pendulums, thermometers, extensometers, extensometers, piezometers, among others, installed at strategic points of the dam, at the time of its construction.

The technical team that performs this monitoring is responsible for establishing, reviewing and disseminating, in the form of reports, the safety levels in which the dam structures are located. Decision-making regarding the safety conditions of the structures based on the analysis of the numerous graphs of the data series of this instrumentation, taking as reference the analytical and constructive conditions established in the dam projects.

Regarding the structural safety of the Itaipu dam, the technical opinion, periodically elaborated by the team of the Center for Advanced Studies in Dam Safety (CEASB), it is based on instrumental measurements, which generate more than 2000 graphs, which when compared to values Specified in the structural design inform the structural conditions of the dam. So far the decision making regarding the data aspect and analyzes of the graphical information are done empirically by the members of the monitoring team. The frequency of measurements and the number of instruments in use since the time of construction of the dam generate an enormous amount of information to analyze regarding the safety of the dam. Therefore, it considered necessary to concentrate this information, in order to speed up the process of identifying anomalies.

Regarding dam monitoring, Cruz (2006) points out that this activity must be performed by a specialized team, through visual inspections, geodetic measurement of vertical and / or horizontal displacements, bathymetric surveys and instrumentation monitoring.

In this task, listening is an integral and extremely important part, considering instrumentation data and visual inspections. The auscultation is composed of a set of ways of observing the behavior of the dam and foundations, to control its safety conditions, to verify the validity of the hypotheses and the calculation methods used in the project and to verify the need for corrective measures (ITAIPU BINACIONAL, 2016).

It is recommended the measurement of values associated with the behaviors: structural (tensions, deformations and displacements); Thermal (concrete temperature, heat dissipation of

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hydration, thermal cycles); Hydraulic and hydrogeological (flow and interstitial pressures); Along with environmental factors influencing dam behavior such as ambient

Reservoir, water level upstream and downstream, precipitation and seismic activity (ELETROBRÁS, 2003; CARVALHO and ROMANEL, 2007; FIORINI, 2008).

The interest in techniques that address the structural monitoring of dams has grown in the last decades, due in particular to the occurrence of accidents, such as ruptures, which resulted in large-scale environmental disasters, financial losses and, often, high death rates. These occurrences prove the importance of developing reliable methodologies to monitor the behavior of the structures that make up the physical part of dams as a way of avoiding the consequences of disasters (MEDEIROS and LOPES, 2011).

In this context, the importance and necessity of using a method of joint analysis of the data to assist in the overall diagnosis of the structural safety conditions of the dam verified. The Joint Monitoring Index Blocks Responses (JMIBR) of dam, was proposed by Oro (2016), for this purpose. The JMIBR is a variable that can't be directly measured and is obtained by means of a model composed of latent variables (factors), originated from observable variables (sensors), taking in to account the action of the ambient temperature and the water level of the reservoir.

In this work, the JMIBR modeling involves the factors associated to the variability of the direct and inverted pendulum data, bystander bases, multiple extensometers of rods and piezometers, installed in two concrete blocks of the dam of the Itaipu Hydroelectric Power Plant.

Regarding the structure of this work, in addition to the already exposed introduction, section 2 and 3 present a theoretical revision regarding dam monitoring and factor analysis, respectively. In the next section, are presented the data and the methodology used in the treatment. Section 5 discusses the results of the factorial analysis applied to the data set and the modeling of the Joint Monitoring Index Blocks Responses (JMIBR) of Itaipu dam.

1 THEORETICAL FOUNDATION

The construction of JMIRB requires the knowledge of the main technical aspects related to the structural monitoring of concrete dams and multivariate statistical methods, especially the factor analysis. These issues are addressed below.

1.1 Concrete dam monitoring

The relationship between a concrete dam and the environment in which is inserted can be represented by an input-output system (Figure 1). Inputs are the environmental variables: ambient temperature around the dam, concrete temperature, water temperature, water level in the reservoir, the downstream water level, rain, earthquake, weather (the work age), among others. The outputs are the dam responses, such as displacement, uplift, leakage, and so on (Cheng and Zheng, 2013).

Among the instruments used in the monitoring of these phenomena are: multiple rod extensometers, piezometers, direct and inverted pendulums, elongation bases and thermometers for concrete.

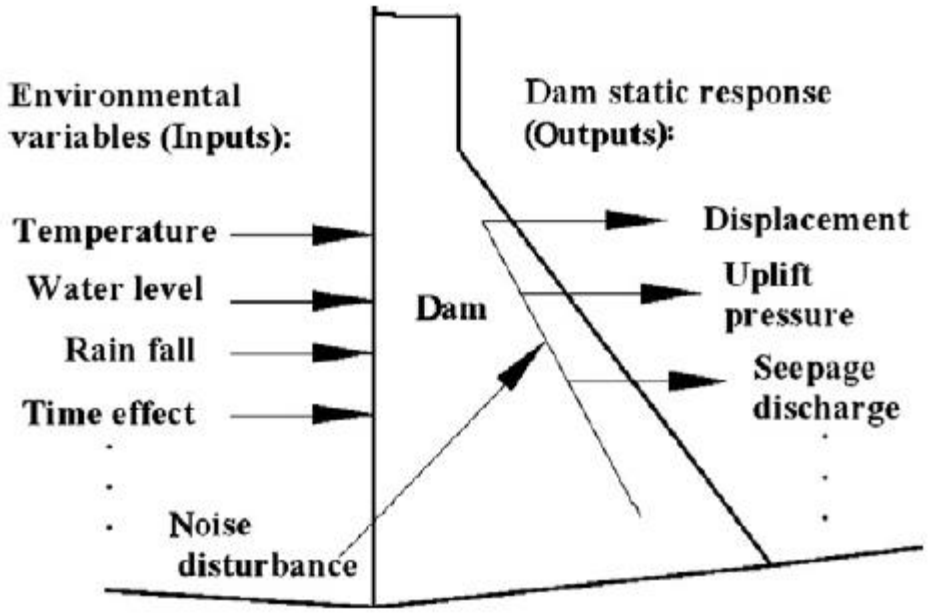


Figure 1. Dam system (CHENG AND ZHENG, 2013)

Multiple rod extensometers allow the measurement of settling and displacement in various areas of the dam foundation, resulting from the action of hydrostatic buoyancy, environmental thermal influences and other constraints. To measure the displacements of the rod extensometers, are used comparator clocks or vibrating string sensors, according to the accuracy and type of reading required.

Another instrument installed in the foundations of dams is the piezometer of the standpipe type, which allows the measurement of the active pressure at the site of its installation (DTI, 2009). In this type of piezometer, the pore water passes through the filter of the instrument's draining bulb until it reaches equilibrium with the pore pressure in the foundation. The pressure then corresponds to the height of the water above the instrument bulb. In general, the median point of the bulb is used as reference for reading (CASTRO, 2008).

The horizontal displacements of the dam are measured by the association of the observed values in the direct and inverted pendulums, and for the measurement of horizontal displacements of the crest are indicated the direct pendulums, while for the shear displacements of the dam base inverted pendulums are used (SILVEIRA, 2003).

Such displacements are mainly affected by the deflection of the concrete structure, the rotation of the base of the structure, due to the deformability of the foundation and the environmental thermal influences. Except for the thermal influences, which operate permanently along the useful life of the work, these displacements evolve more strongly in the first years after filling the dam reservoir, tending exponentially to a stabilized value over time (CHI, 2002).

In the installation of the direct pendulum one end is fixed to the crest of the dam going to the concrete-rock contact, whereas the inverted pendulums are fixed in the foundation going to the concrete-rock contact, and the installation depth of the inverted pendulums is conditioned to the Height of the dam and the sub-horizontal discontinuities of the foundation. Preferably,

both must be installed in the same key blocks of the dam, so that it is possible to compare the values of the horizontal displacements of the direct / inverted pendulums with those obtained geodesically (MATOS, 2002).

In order to follow the displacements between two adjacent blocks, separated by a contraction joint, an elongometer supported on triangular bases of reference previously fixed on the surface of the concrete is used. The measured values allow to follow the behavior of the structures during the periods of construction, hydrostatic loading and in the operation phase of the reservoir (SOM, 1990b).

The elongation bases make it possible to measure horizontal and vertical relative displacements between the joints of the dam blocks. The reading is made by a portable device coupled to a dial indicator.

For the measurement of the displacements, two readings are made at each base of an elongate: one of the measurements corresponds to the opening or closing of the joints, while the other measure indicates the sliding between the blocks. The sliding, in turn, according to Neumann Jr (2015), can be interpreted in two ways, depending on whether the lengths are installed in the wall or in the floor of the galleries of the structure. When on the floor, the slip indicates a relative upstream-downstream movement. When on the wall, this would correspond to a relative repression between the blocks.

1.2 Factor Analysis

Multivariate analysis provides methods and techniques for the theoretical interpretation of a sample comprising several observations for two or more variables.

A collection of *n* observations on *p* distinct random variables, taken from the same item, composes a multivariate sample, which can be represented by an *X* matrix (Eq. 1), such that the rows correspond to the observations and the columns to the variables.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1p} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{ip} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nj} & \dots & x_{np} \end{bmatrix} \quad (1)$$

According to Lattin, Carrol and Green (2011), the selection of the variables of a process can be done from p correlated variables and, by the application of the factorial analysis, we obtain a set of m unrelated latent variables ($1 < m < p$), called common factors, which have special properties in terms of variances.

Through factor analysis it is possible to obtain the description of matrices with lots of elements in an exploratory manner (without having prior knowledge of the structure), and view the most important relationships of an extensive set of variables with each other or the relationship between the samples and variables.

Initially, one must select the variables *p*, define the sample size *n*, perform the data sampling and organize them in matrix form (Eq. 1). According to Hair et al. (2009), the sample size should be at least 5 times the number of variables, the most acceptable ratio was 10 to one.

If any differences in measurement scales or quantities, Mingoti (2005) indicates use standardized variables (Eq. 2), whose variance is unity, because thus there is no direct dominance of any of them.

$$z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j}\ ,\ \ i = 1, 2, \ldots, n \quad \text{and} \quad j = 1, 2, \ldots, p \tag{2}$$

Where,

$\bar{x}_j$ is the sample mean;

s_j is the standard deviation.

Application of factor analysis may be made from the covariance matrix (Eq. 3) or correlation (Eq. 4). When choosing the matrix of sample correlations, the factors weighting coefficients will be more balanced than those obtained from the covariance matrix (MINGOTI, 2005).

$$\hat{V}(\underline{X}) = S = \begin{bmatrix} s_1^2 & s_{12} & \ldots & s_{1j} & \ldots & s_{1p} \\ s_{21} & s_2^2 & \ldots & s_{2j} & \ldots & s_{2p} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_{j1} & s_{j2} & \ldots & s_j^2 & \ldots & s_{jp} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_{p1} & s_{p2} & \ldots & s_{pj} & \ldots & s_p^2 \end{bmatrix} \tag{3}$$

Where,

$s_{jk} = \frac{1}{n-1}\sum_{i=1}^{n}(x_{ij} - \overline{x}_j)(x_{ik} - \overline{x}_k)$ is the sample covariance between the variables x_j and x_k, with $j, k = 1, 2, \ldots, p$, for $j \neq k$;

s_j^2 is the sample variance of the variable x_j, with $j = 1,2, \ldots, p$.

$$\hat{\rho} = R = \begin{bmatrix} 1 & r_{12} & \ldots & r_{1j} & \ldots & r_{1p} \\ r_{21} & 1 & \ldots & r_{2j} & \ldots & r_{2p} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ r_{j1} & r_{j2} & \ldots & 1 & \ldots & r_{jp} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ r_{p1} & r_{p2} & \ldots & r_{pj} & \ldots & 1 \end{bmatrix} \tag{4}$$

Where,

$r_{jk} = r_{kj} = \frac{s_{jk}}{\sqrt{s_{jj}}\sqrt{s_{kk}}}$ is the sample correlation between the variables x_j and x_k, with $j, k = 1, 2, \ldots, p$, for $j \neq k$.

In the factor analysis, the eigenvalues arranged in ascending order corresponding to the factor variances, allowing the formation of self-spaces associated with eigenvectors and hence the factor plans, which are two-dimensional subspaces. Thus, it is possible to reduce the number of dimensions of space with which you are working, obtaining a representation of the samples

spaces and variables in this smaller space. The number of factors can be selected according to the number of eigenvalues of the correlation (or covariance) matrix that are larger than the unit.

The result is an orthogonal factorial model (Equations 5), composed of *m* common factors and their respective factorial loads (Equation 6), together with the measures of commonalities (Equation 7) and specific variances (Equation 8) of the *p* random variables standardized.

$$\underline{Z} = L\underline{F} + \underline{\varepsilon} \tag{5}$$

Where,

$\underline{Z}$ is the vector containing the standardized sample data;

L is the matrix of factorial loads, composed of the elements l_{jk};

$\underline{F}$ is the vector of factors;

$\underline{\varepsilon}$ is the residual vector.

$$l_{jk} = cov(Z_j, F_k) \tag{6}$$

Where,

l_{jk} is the load factor (correlation) between the standardized variable Z_j and factor F_k with $j = 1, 2, ..., p$, and $k = 1, 2, ..., m$.

$$h_j^2 = l_{j1}^2 + l_{j2}^2 + \cdots + l_{jk}^2 + \cdots + l_{jm}^2 \tag{7}$$

Where,

h_j^2 is a measure of the *j-th* variable community, $j = 1, ..., p$, and .

$$\psi_j = s_j^2 - \sum_k^m l_{jk}^2 \qquad , j = 1, \dots, p \tag{8}$$

Where,

ψ_j is the measure of the specific variance of the *j-th* variable, with $j = 1, ..., p$ and $k = 1, ..., m$.

The factor load reflects the extent to which each common factor contributes to the variance of the observations in each variable. If the researcher is working with standardized data, then the parameter l_{jk} is the coefficient of correlation of the fator F_k with the variable Z_j. The commonality is the portion of the variance of each original variable from the extracted factors. The remainder of the variability, which may be due to specific factors, is measured by the specific variance.

The interpretation of the common factors using the matrix of factorial loads can be a difficult task. However, it is possible to choose a different orientation by rotating the factorial solution appropriately to obtain an array of factorial loads with a simpler structure to be interpreted (HAIR et al., 2009).

The most popular rotation is the Varimax. It is an orthogonal transformation of the original factors, which occurs through the selection of coefficients that maximize the variation of the squares of the original factorial loads, thus enabling to obtain for each factor a group of variables highly correlated with a factor and with correlation negligible or moderate with other factors.

1.3 Joint Monitoring Index Blocks Responses of Dam

The factors resulting from the application of the factorial analysis to the monitoring data are quantitative variables that are related to the variability of the dam responses. These factors are the parameters and the respective factor scores are the input data used for the modeling of the Barracks' Joint Response Response Index (ORO, 2016).

The IMCRB concentrates the information of the factors that, in turn, represent the set of observations of the sensors used to monitor the movements of the dam and the environmental conditions around it, with minimal loss of information.

The model for the IMCRB (Eq. 9) is relatively simple, consisting of the weighted average of the factors, taking the eigenvalues of the correlation matrix as weights.

$$IMCRB_i = \frac{\sum_{k=1}^{m} \lambda_k f_{ik}}{p} \quad com \;\; i = 1, 2, \dots, n \tag{9}$$

Onde:

λ_k is the *k-th* eigenvalue of the correlation matrix;

f_{ik} is the *i-th* score of the *k-th* factor;

p is the number of original variables (sensors);

n is the number of observations taken for each variable.

This index, whose value is dimensionless, is a time series with the same size of the sample set used in the modeling. According to ORO (2016), the factors are also time series and, therefore, it is advisable to verify the stationarity of these series. When a series of one factor is considered to be non-stationary, the number of differentiations needed to make it stationary must be realized, and to work with the differentiated series in the IMCRB modeling.

2 MATERIALS AND METHODS

The data set considered in this work is composed of the monthly averages of values measured manually in the instrumentation of blocks D7 and D8, of Section D, of the Itaipu Hydroelectric Power Plant, in the period from January 1990 to December 2015. This period was selected because before 1990 the dam still reflected the effects of reservoir construction and filling.

These blocks (Fig. 2 and 3) are located in the Right Lateral Dam and have the following structural characteristics: blocks of buttresses with 17 m of width on the axis and height ranging from 35 to 52.5 m; polygonal head of the concrete-mass buttress; slope of upstream and downstream equals those of the Main Dam; upright head such as the quadrant of a circle, free

of internal tensile stresses; of the buttress with increasing thickness horizontally from the neck to the downstream face and in the vertical direction from the 201.5 m elevation to the foundation (SOM, 1984).

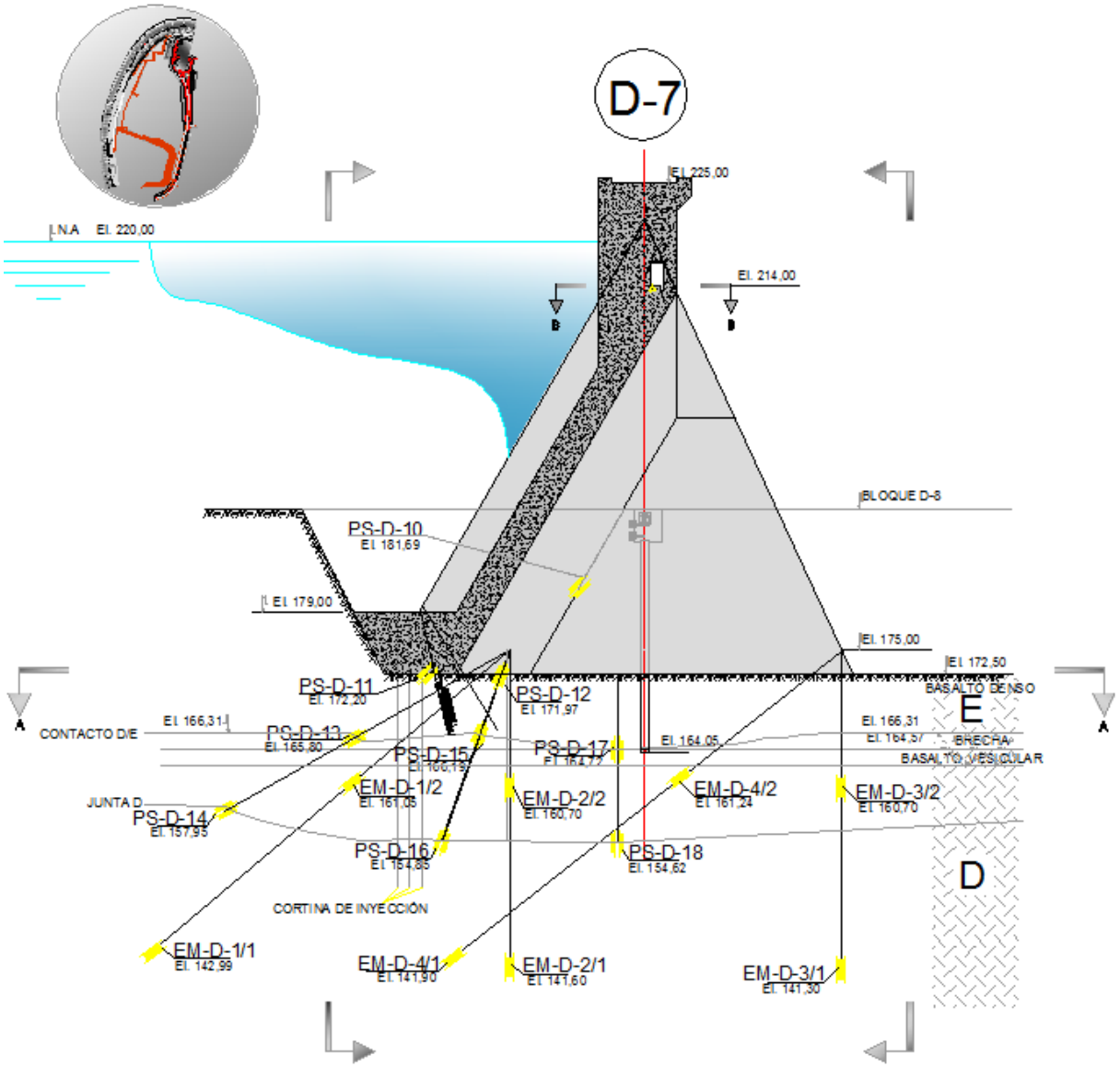


Figure 2. Block D7 of Itaipu Dam

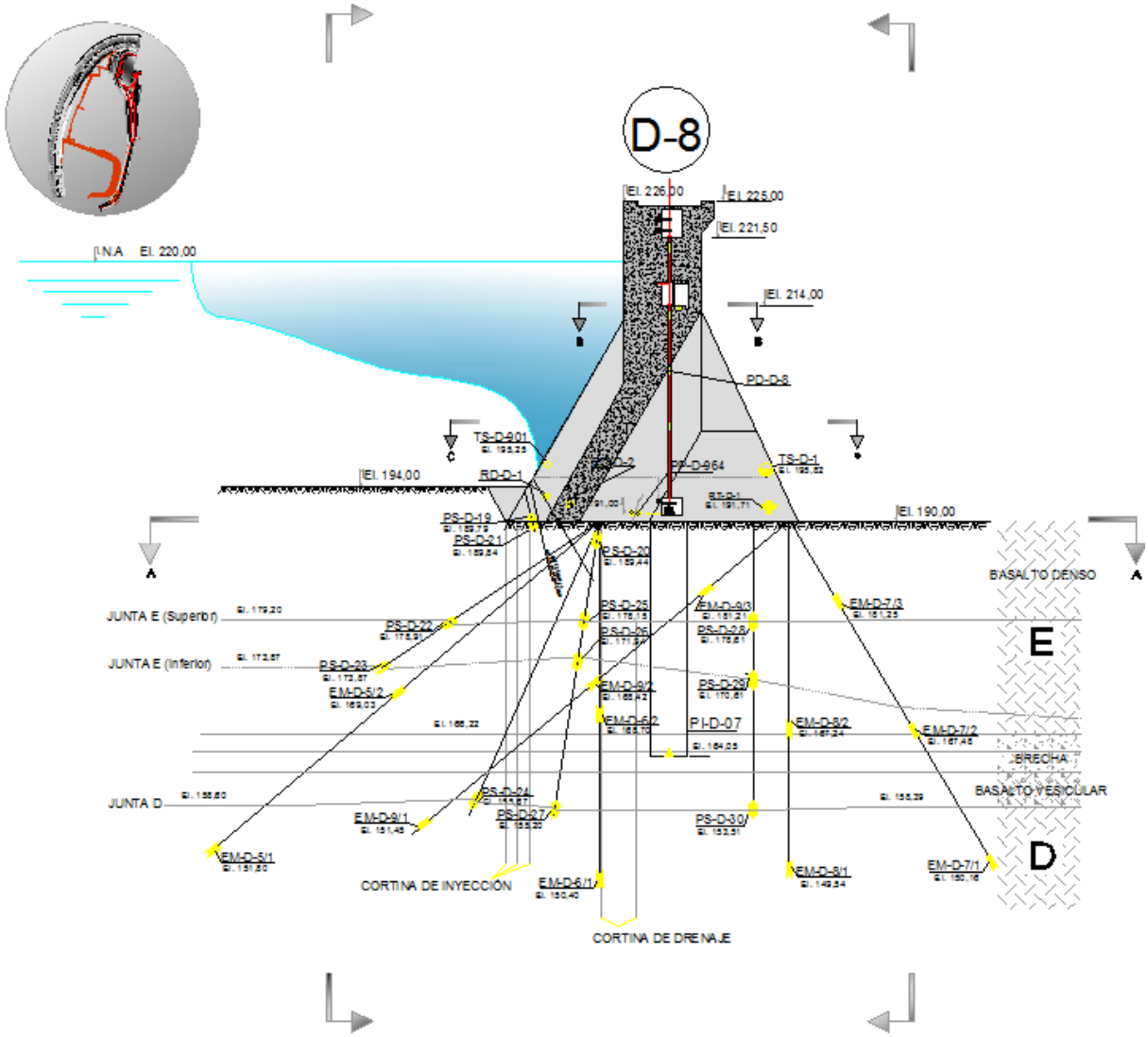


Figure 3. Block D8 of Itaipu Dam

In this study we considered the direct and inverted pendulums, extensor bases, multiple extensometers of rods and piezometers. We chose these instruments because they allow to follow the occurrence of the following phenomena: radial displacement, tangential displacement, opening between blocks, horizontal sliding between blocks, settlements, deformations of the rock mass and underpressure.

Thus, 50 sensors (hereinafter referred to as variables) were selected from 63 available. The 13 unused sensors correspond to thermometers, limnimetric ruler and some piezometers. The first two were excluded because they were hydrometeorological sensors and the last two because they had some strange characteristic, such as constant values over time.

To verify the feasibility of using the factorial analysis the Bartlett sphericity test was applied, testing the hypothesis that the correlation matrix was equal to the identity matrix. The correlation matrix also served as the basis for the calculation of the KMO coefficient, which is

the other technique for checking the suitability of the sample for the application of the factorial analysis.

The method used to determine the number of factors was the Horn Parallel Analysis and the percentage of explanation of the same. The method of factor extraction adopted was by main components, because this does not require that the variables be normally distributed. The correlation of the variables with each factor was measured by the factorial loads, resulting from this decomposition. To facilitate the interpretation of the factors, the orthogonal transformation called the Varimax rotation was used, so that each sensor presented high loads in one factor and reduced in the others.

In the context of this study, the measure of commonality reflects how much of the variance of the sensor is due to the factors, thus representing the quality of the adjustment of the factorial model to the data and, mainly, the importance of the instrument in the context of the analysis. Using the commonality as a measure that distinguishes the behavior of the sensor, we proceeded to the hierarchization of the sensors.

As the factors can not be directly measured, their values, called factor scores, were estimated using the matrix of factor loads and the sample data. These scores formed the input data set used in the IMCRB modeling.

3 RESULTS AND DISCUSSION

Initially, the correlations between the sensors were estimated. To verify the significance of the correlations, Bartlett's sphericity test was applied. The calculated value for the T statistic (36625.78) was much higher than the critical value at 95% confidence (1307.54), indicating that collectively the sensors were significantly intercorrelated, which allowed the application of the factorial analysis.

The result obtained for the KMO coefficient (0.94) showed an excellent suitability of the sample for the factorial model.

The factorial analysis was then applied to the correlation matrix of the 50 standard variables, with the objective of identifying the factors that can be used as parameters for the elaboration of the Joint Monitoring Index Blocks Response (JMIBR) of the Dam.

Horn's parallel analysis indicated that 4 factors would be sufficient to represent the set of variables and explain approximately 87% of the observed variance of the data set.

The factors were named according to the sensors most correlated with them, that is, according to the highest factor loads (Fig. 4). The first factor (F1), identified as "Opening between Blocks", was named because it is mainly correlated with the bases of an extension and with the pendulums in the right-left direction. This was the most important of the factors extracted, since it answered for 26% of the observed variability in the data set.

The second factor (F2) explained about 23% of the variance and was associated with the sensors of 6 rods of extensometers and with a pendulum upstream-downstream, so it was called "Rotation".

Loadings:

	F1	F2	F3	F4
Z1	0.522	0.218		0.333
Z2	0.790	0.406	-0.224	
Z3	0.490	0.682	-0.421	-0.196
Z4	0.806	0.298	0.263	
Z5	0.503	0.707	-0.348	-0.114
Z6	0.828	0.238	0.164	0.161
Z7	0.953	0.166	-0.183	-0.117
Z8	0.465	0.234	0.544	0.422
Z9	0.963	0.116	-0.208	
Z10	-0.178		0.857	0.185
Z11	0.894		-0.247	-0.206
Z12	-0.732	0.119	0.507	0.344
Z13	0.956	0.223		
Z14	-0.550	0.329	0.506	0.429
Z15	0.961	0.153	-0.163	
Z16	0.814	-0.206		
Z17	0.939	0.210	0.164	
Z18	-0.467	0.293	0.279	0.571
Z21		0.358	0.736	0.452
Z22	0.261	0.462	0.657	0.445
Z23	0.426	0.856		
Z24	0.486	0.841		
Z25	-0.272	0.494	0.685	0.422
Z26	-0.215	0.573	0.662	0.351
Z27	0.241	0.710	0.562	0.178
Z28		0.606	0.640	0.273
Z29	-0.137	0.174	0.785	0.421
Z30	-0.121	0.178	0.785	0.367
Z31	-0.408	0.797	0.237	0.250
Z32	-0.399	0.799	0.277	0.208
Z33	0.308	0.660	0.572	0.357
Z34	0.335	0.635	0.613	0.303
Z35	0.527	0.752	0.348	0.120
Z36		0.742	0.576	0.297
Z37		0.757	0.543	0.272
Z38		0.896	0.244	0.248
Z39		0.838	0.370	0.288
Z40	0.227	0.915	0.152	
Z44	0.101	0.216	0.247	0.731
Z48	-0.180		0.524	0.715
Z50	-0.178		0.479	0.760
Z51			0.320	0.897
Z52	-0.790	0.188	0.185	0.209
Z55	0.662		0.190	0.402
Z56	0.126			0.882
Z58	-0.189	0.214	0.630	0.528
Z59		0.135	0.345	0.919
Z60		0.185	0.372	0.752
Z62		0.130	0.339	0.919
Z63	0.268	-0.186	-0.673	-0.500

	F1	F2	F3	F4
SS loadings	12.901	11.490	9.872	9.076
Proportion Var	0.258	0.230	0.197	0.182
Cumulative Var	0.258	0.488	0.685	0.867

Figure 4. Loadings of factors

The "", third factor identified (F3), was responsible for approximately 20% of the variability. The dominant variables in this factor were a sensor of the base of measure that measures repression and some rods of extensometers.

Most piezometers showed a high correlation with the fourth factor (F4). For this reason, it has been identified as "Subpress". This last factor accounts for approximately 18% of the observed variability in the data set.

The variability present in the readings of each sensor, derived from the factors identified, was estimated through commonality (Fig. 5), because the larger this measure, the smaller the specific variance. Using this information as a measure of the importance of each variable for the factorial model, we obtained the ranking of the sensors. Thus, the most important instruments for blocks D8 and D7 were the Z33, Z34, Z35 multiple strain gauge rods, the Z7, Z9 (opening joints between blocks) and Z59 piezometer bases.

Communality

Z1	Z2	Z3	Z4	Z5	Z6	Z7
0.4308537	0.8398072	0.9215323	0.8150677	0.8860833	0.7949731	0.9829338
Z8	Z9	Z10	Z11	Z12	Z13	Z14
0.7454804	0.9881225	0.8067423	0.9027713	0.9242078	0.9646840	0.8501302
Z15	Z16	Z17	Z18	Z21	Z22	Z23
0.9795077	0.7123913	0.9527657	0.7075607	0.8775750	0.9111550	0.9188032
Z24	Z25	Z26	Z27	Z28	Z29	Z30
0.9478835	0.9651538	0.9361755	0.9101173	0.8598375	0.8428543	0.7974881
Z31	Z32	Z33	Z34	Z35	Z36	Z37
0.9195446	0.9179481	0.9840258	0.9822923	0.9790932	0.9712964	0.9453781
Z38	Z39	Z40	Z44	Z48	Z50	Z51
0.9265266	0.9229179	0.9186618	0.6523475	0.8234834	0.8427438	0.9194587
Z52	Z55	Z56	Z58	Z59	Z60	Z62
0.7372082	0.6430886	0.8013910	0.7580586	0.9838492	0.7479754	0.9798841
Z63						
0.8087769						

Figure 5. Communality of sensors

The three rods with the largest commonalities have the characteristic of being installed in the same drilling hole downstream, in the foundation of block D8, from the elevation 191 m, very close to the place where the piezometer and the two bases are installed. which measure the underpressure in the foundation and the opening of the joints between blocks D7 and D8 (Z7 and Z9), respectively. This result is identical to that obtained by ORO (2016). Which indicates that these sensors are really very important.

Considering that the four factors identified are quantitative variables that are related to the variability of the dam responses, they were used as parameters for the elaboration of the Joint Monitoring Index Blocks Response of the Dam.

The Figure 6 shows the time series of factors used in the modeling of the JMIBR. It is noticed that there is no tendency and that the series is stationary in the average, not being necessary the realization of differentiation.

The Joint Monitoring Index Blocks Responses of the dam was formulated (Eq. 10) through the weighted average of the factor scores, with weights stipulated by the eigenvalues of the sample correlation matrix. The series obtained for the JMIBR (Fig. 7) is also stationary and presents seasonality, as well as most of the sensors considered in this study.

$$JMIBR = 0.30F1 + 0.27F2 + 0.23F3 + 0.21F4 \quad (10)$$

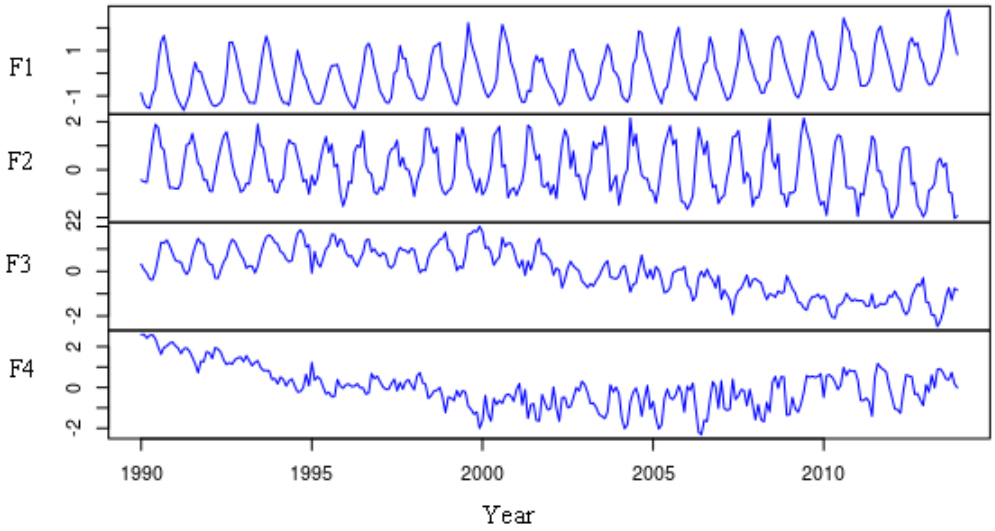


Figure 6. Time series of factors

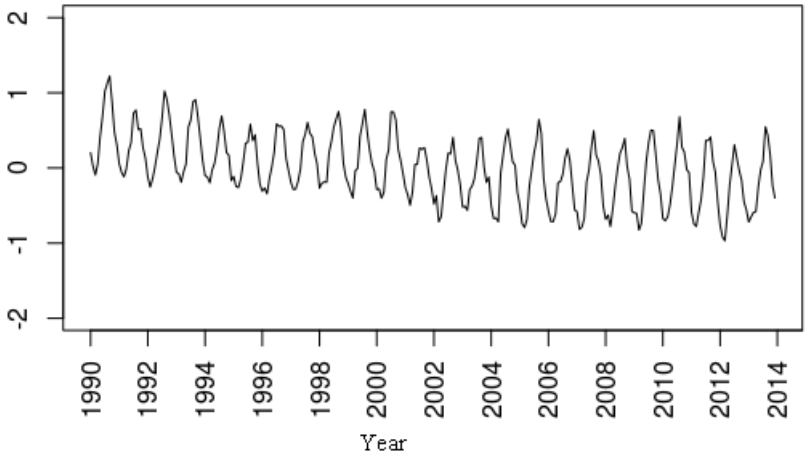


Figure 7. Time series of JMIBR

CONCLUSION

Most of the variability of the data of the 50 sensors considered in this study was identified, through the application of the factorial analysis, as coming from the following factors: Opening between Blocks; Rotation; Upright and Underpressure. These factors can be used as parameters to obtain the Joint Monitoring Index of the responses of blocks D7 and D8 of the dam.

The main contribution of this work was the modeling of the JMIBR with the inclusion of piezometers and without considering any type of environmental variable. For future work, it is suggested to consider the time lag of the values obtained for the JMIBR and to add to the model other variables, such as hydrometeorological.

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