ANALYSIS OF IRREVERSIBLE DISPLACEMENTS IN MULTIPLE ARCH CONCRETE DAM USING PRINCIPAL COMPONENT ANALYSIS

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ABSTRACT

Irreversible displacements are important to quantify in the assessment of the behavior of concrete dams. Irreversible displacements can manifest themselves immediately during the first filling of the reservoir or a later date during the service life of the structure. Irreversible displacements are usually associated with settlements of the foundation, creep of the concrete, or chemical reactions associated with material properties, such as the alkali-aggregate reaction. Linear regression models are commonly used to analyze displacement data from monitoring instruments and to separate the response into hydrostatic, seasonal and irreversible components. However, linear regression requires some assumptions relative to the form of the models and cannot distinguish between the contributions from the various sources of irreversible displacements. Multivariate statistical analysis procedures are proposed as an alternative to linear regression analysis. The proposed methods offer the advantage of being nonparametric and can be used to analyze components of displacements from several instruments simultaneously and identify components of behavior that are highly correlated across the entire structure. The procedure is presented and applied to the analysis of the displacement data for a multiple arch dam. The method identifies the principal modes of deformation of the dam associated with thermal, reservoir and irreversible effects. The irreversible displacements can be further separated in components that can be associated with creep and swelling, which is an improvement over linear regression analysis procedures.

KEYWORD

Decision support systems, Monitoring, Infrastructure, Instrumentation, Modeling

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1. INTRODUCTION

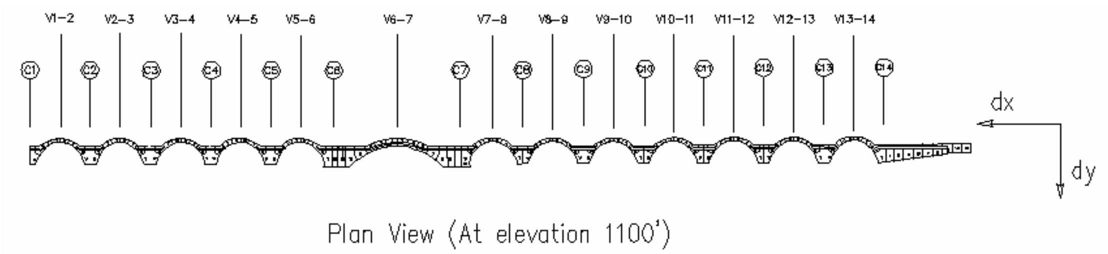
The objective of this paper is to demonstrate the benefits of multivariate statistical analysis to study the long term behavior of a structure. The demonstration of the procedures is performed with displacement data obtained from pendulums at the Daniel Johnson Dam, a multiple arch concrete dam in the province of Québec. The objectives of the analyses are to estimate the components of behavior of the dam and to determine the significance, extent and type of irreversible displacements. The analysis was performed by using the following steps:

1) A standard linear regression analysis was performed for each component of displacements from individual pendulums (x: along the axis of the dam, y: upstream to downstream, z: vertically) using the Hydrostatic, Seasonal, Time (HST) model (Chouinard and Roy 2006). The objective of this analysis is to identify the major factors that control individual displacements. The results of the analysis are also used to identify faulty instruments, faulty readings, and to replace missing values with predicted values. In the course of this research, a computer program DASOD was developed to review the observed data, perform the statistical analysis with the HST method, visualize the analysis results in plan and elevation views of the dam, and prepare input data files for the multivariate statistical analysis.

2) Displacements from individual pendulums were compiled in a single data set and a Principal Component Analysis (PCA) was performed. The results of the PCA are analyzed to retain the components that are statistically significant. The scores of each component are then analyzed and interpreted in terms of the structural response of the dam.

2. DESCRIPTION OF DANIEL JOHNSON DAM

The Daniel Johnson Dam, located in the north of the province of Quebec, is a multiple-arch concrete dam. It has 13 arches and 14 buttresses, and a height of 214 m at its highest point (Figure 1).



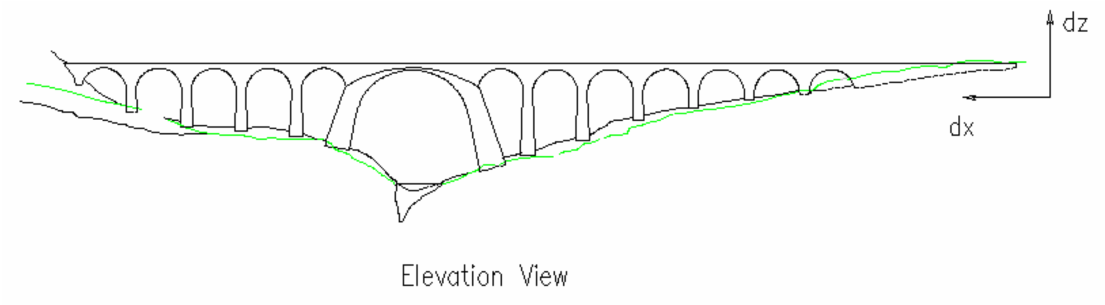


Figure 1 Plan and Elevation Views of Daniel Johnson Dam.

The dam has been continuously monitored since its construction with numerous instruments (pendulums, thermometers, flow meters, etc.). Three data sets were used in the analysis : (1) data on the water level of the reservoir, (2) data on air temperature, and (3) data on pendulum displacements.

A total of 96 pendulums were installed in the buttresses and arches to monitor the deformations of the dam. Each pendulum can measure displacements in three directions (dx, dy and dz) except for those in the arches (dx and dy only). The convention for positive displacements in the dx, dy, and dz directions are shown in plan and elevation views of the dam (Figure 1).

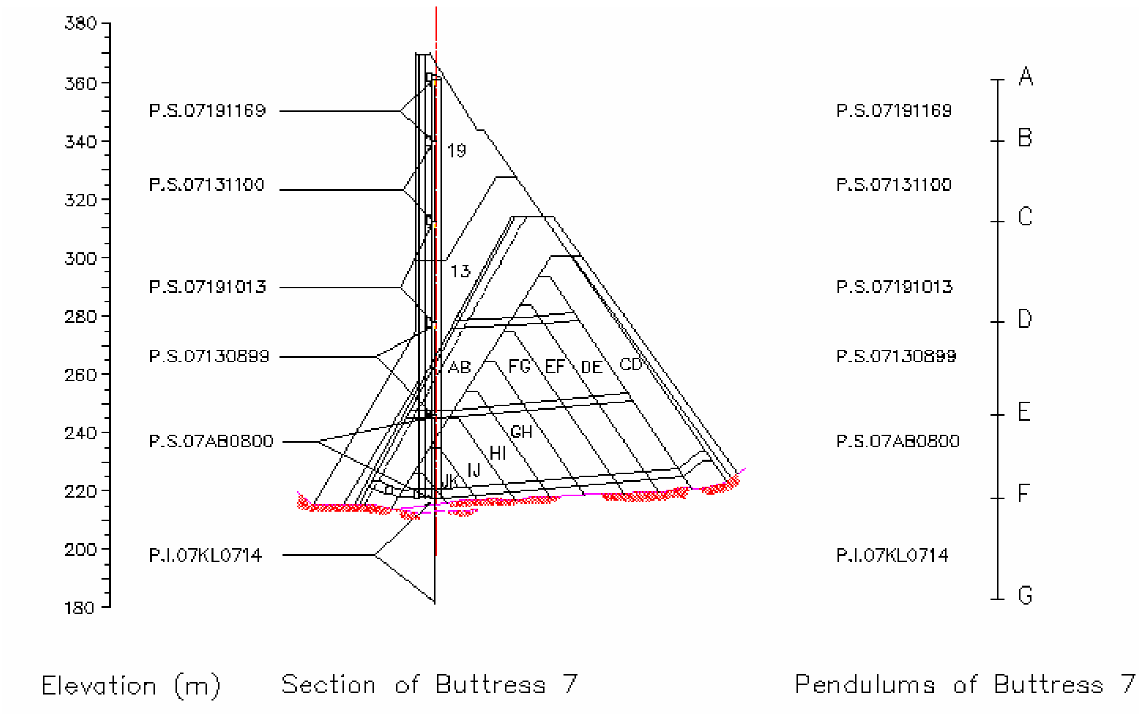


Figure 2 Pendulums in Buttress 7

Figure 2 shows a typical installation for a sequence of pendulums in series in one of the buttresses. There are 6 pendulums from bottom to top and the bottom pendulum is inverted while the others are simple pendulums. Each pendulum measures differential displacements in three directions between its two ends. Deformation for the purpose of the analysis is defined as the displacement per unit length of the pendulum. Local displacements are defined as displacements between two ends of a pendulum and global displacements as displacements between the top of a pendulum and a reference point at the base of the sequence of pendulums, point G in Figure 2).

ANALYSES FOR INDIVIDUAL MEASUREMENTS

Dams are subjected to three factors: the hydrostatic load from the reservoir, air (and water) temperature and time. Effects from the hydrostatic load and temperature are usually assumed to be reversible and only time effects are irreversible. Analysis for individual instruments and components of displacements are usually performed with linear regression, which requires a parametric model for each effect. The HST (Hydrostatic-Season-Time) model is a simple regression model that was first developed by Willm and Beaujoint (1958) and that is widely used for analyzing displacement data of concrete dams (Chouinard and Roy 2006).

$$MB_j = f_1(H_j) + f_2(S_j) + f_3(t) + r_j$$

Figure 3 Vectors of irreversible deformation rate in the x-y plane.

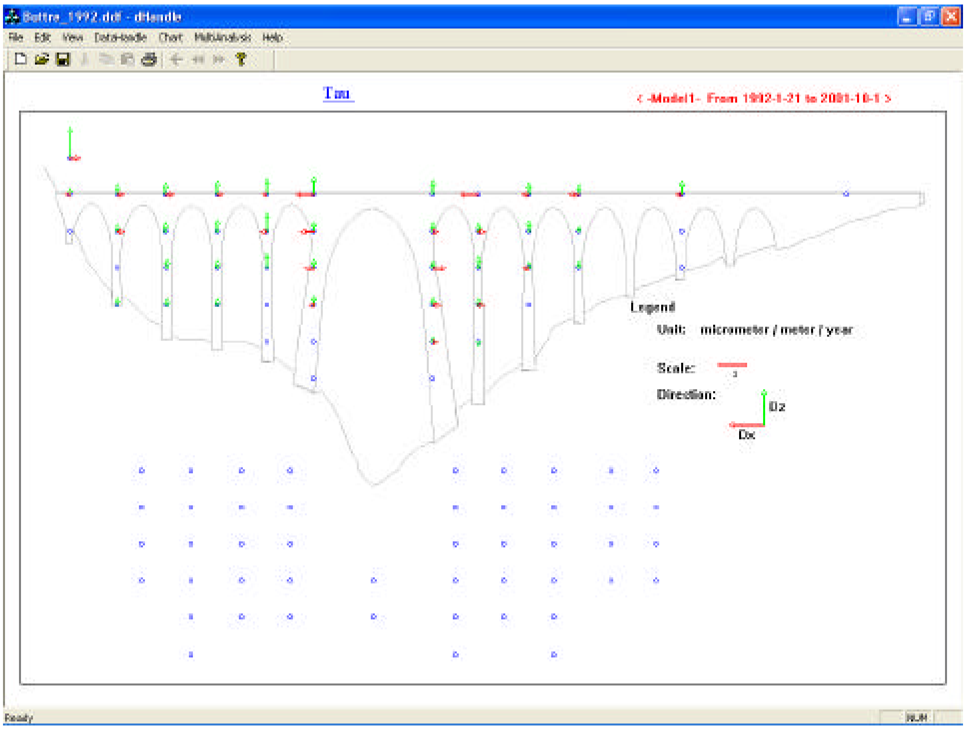


Figure 4 Vectors of irreversible deformation rates in the x-z plane.

This model was used as a preliminary step to the multivariate statistical analysis. First, the model is useful to sort out instruments that exhibit erratic behaviour. In theory, multivariate statistical analysis procedures are robust and can sort out erratic instruments directly; however, the analysis per instrument is performed on a routine basis and faulty instruments should be removed from the data when they have been clearly identified. Similarly, the HST model can be used to eliminate observations that are clearly outliers. Finally, the model was used to complete the time series when simultaneous observations were missing on instruments selected for the multivariate statistical analysis. The results of the analysis per instrument indicate that seasonal effects are the most important components of the deformations, followed by hydrostatic effects and irreversible effects.

Figures 3 and 4 show the rate of irreversible displacements obtained from the HST model for selected pendulums on plan and elevation views of the dam (period 1992-2001). The results hint to the presence of a slow swelling process. Irreversible displacements that are both upwards and upstream are typical for dams affected by the alkali-aggregate reaction.

ANALYSES ON MULTIPLE SIMULTANEOUS MEASUREMENTS

Multivariate statistical analysis was applied to the group of instruments that exhibit a good response according to the HST model. For the analysis, the three components of displacements (xyz) for each pendulum are considered as separate variables. The objective of the analysis is to determine the dominant patterns of displacements of the dam in three dimensions.

Principal component analysis, a method of multivariate analysis, can be used to both compress the original data and to characterize the global behavior of the dam (Nedushan 2003). Assuming that the analysis is performed on p variables each with n simultaneous observations, the observations are first grouped into a matrix F of dimensions (p x n). The covariance matrix S (p x p) can is estimated from,

$$S = \frac{FF^T}{n-1}$$

The correlation matrix R for the variables can be obtained from the covariance matrix by dividing each component by the standard deviation of the variables corresponding to given rows and columns.

An eigenvalue/eigenvector decomposition of the matrix S or R is performed and the eigenvalue/eigenvector pairs are ordered in descending order: ($?_1$, e_1), ($?_2$, e_2), … , ($?_p$, e_p), where $?_1$ = $?_2$ = … = $?_p$ = 0. The eigenvectors can be viewed as coefficients in a linear combination of the original variables, that define a new set of variables, Y_1, Y_2,…, Y_p that are mutually uncorrelated.

$$Y_i = e_i^T \cdot X$$

The variables Y_1, Y_2,…, Y_p are the principal components of the original variables. Principal components have the following characteristics: (1) All principal components are uncorrelated to each other, (2) The variance of a principal component is equal to its eigenvalue, and (3) The first k (k < p) principal components are the ones that explain most of the variance of original variables.

The procedure was applied to various groupings of instruments defined in terms of their year of installation, frequency of readings and location. The main groupings of instruments are in terms of those that are read manually or automatically, and those that are located in the buttresses or the arches. The results that are discussed in this paper are restricted to a group of pendulums that are read automatically and are located in the buttresses.

Table 1 shows the first six eigenvalues for 37 displacements variables obtained from the specified group of pendulums. The first three principal components explain most of the variance (94%) of the original variables. Figure 5 presents the matrix scatter plot of the first three principal components, water level, and air temperature. The first component explains 69.5% of the total variance, and its scores are correlated with air temperature (Figure 6). The scores of the second component (19.5% of the total variance) are also correlated with air temperature (Figure 6). Note that there exists a lag between scores of the first and the second component and air temperature. The lag is due to the thermal inertia between fluctuations of air temperature and fluctuations of temperatures inside the dam. The first component is correlated with the dominant temperature response among the 37 displacements used in the analysis. The second component corresponds to the second dominant thermal response that is uncorrelated with the first component. Note that the analysis is nonparametric in the sense that there are no assumptions relative to the relationship between the components and the independent variables. Both factors have yearly cycles that approach a sinusoidal variation.

Table 1 Principal Components of Automatic Displacement

Principal components	Eigenvalue	% Total variance	Cumulative %
1	25.71	69.49	69.49
2	7.20	19.45	88.94
3	1.85	5.01	93.95
4	0.96	2.59	96.54
5	0.54	1.45	97.99
6	0.29	0.78	98.77

An important feature of the scatter plot between the two first principal components is that there is a functional relationship between the two components that is nonlinear. With a proper modification to the original data it is possible to account for this nonlinear relationship or to eliminate it. The nonlinear relationship in this case is associated with the lags between the thermal responses of the instruments. One solution is to shift the time series of the instruments to eliminate the lag or simply to remove the seasonal effect. The latter is simpler since it does not require the estimation of the lag and can be done by using the results from the HST model. After elimination of the thermal components, only the effects associated with the water reservoir level and time remain.

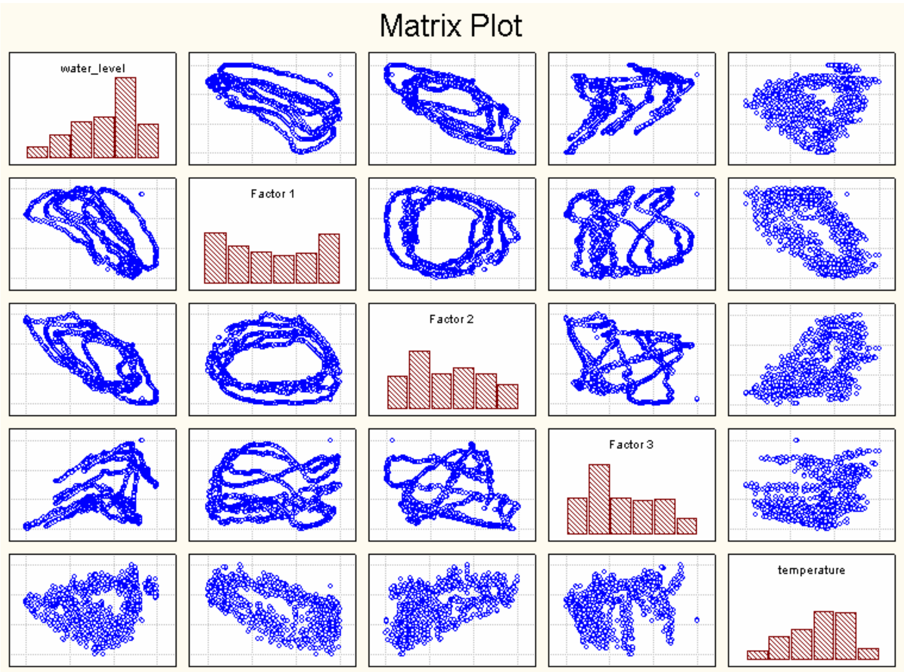


Figure 5 Matrix Plot of Principal Components, Water Level and Air Temperature for Automatic Displacements

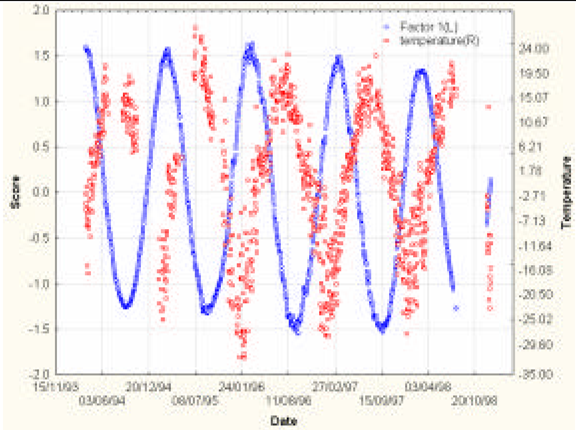


Figure 6 Scores for the First Principal Component and Air Temperature as Function of Time.

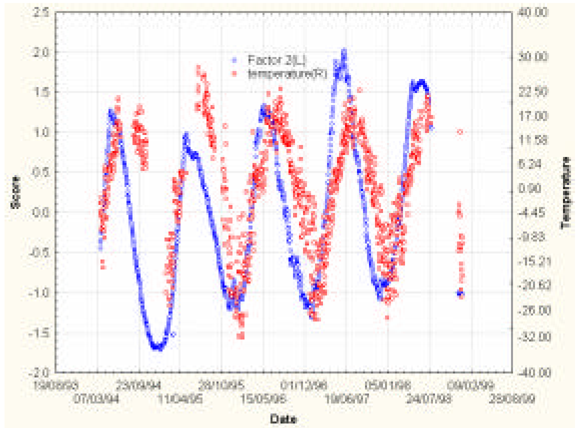


Figure 7 Scores for the Second Principal Component and Air Temperature as a Function of Time.

The first seven eigenvalues of the PCA for displacements without the seasonal effect are shown in Table 2. The first six components explain 92% of the total variance, while the first three components explain 82% of the total variance.

The matrix plot shows that there is a slightly nonlinear relationship between the first principal component (49.1% of the total variance) and water level, which means that the displacement caused by the water level is second in importance for displacements (Figure 8). The second component explains 25.6% of the variance, and its scores are correlated with time. (Figure 9) The second component appears to be mainly related to irreversible displacements in the dam. The trend of irreversible displacements is linear with some small dependence with reservoir water level. Higher order components could be statistically significant; however, their interpretation is more difficult and represents minor features of the overall behavior of the dam since the seasonal effect and the first two components explain more than 97% of the total variance of displacements.

Table 2 Principal Components of Automatic Displacements (without Seasonal Effect)

Principal components	Eigenvalue	% Total variance	Cumulative %
1	18.14862	49.05033	49.1
2	9.46153	25.57171	74.6
3	2.64605	7.15149	81.8
4	1.82434	4.93066	86.7
5	1.07810	2.91379	89.6
6	0.85379	2.30754	91.9
7	0.47171	1.27489	93.2

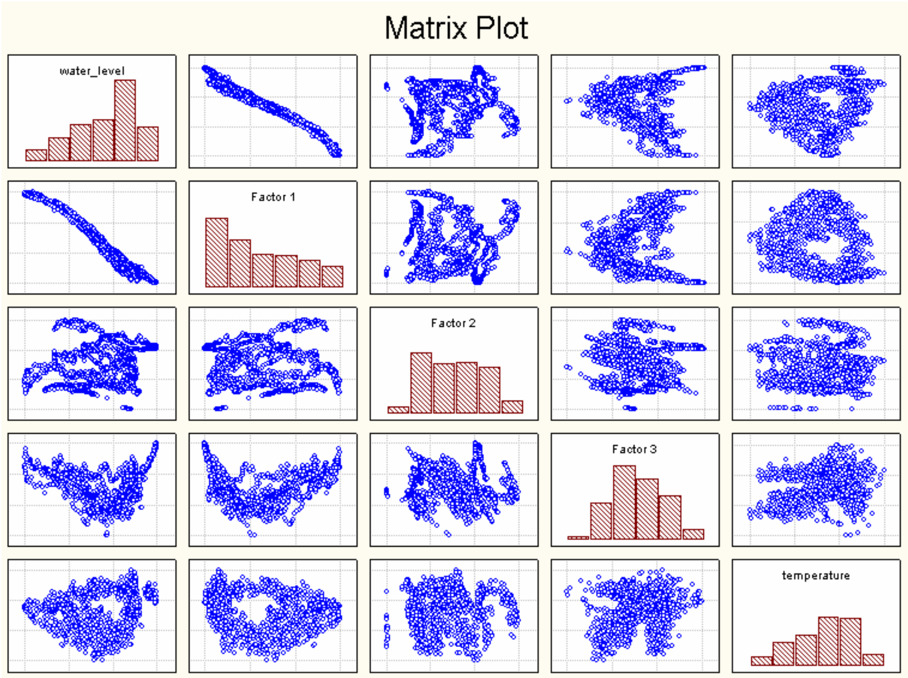


Figure 8 Matrix Plot of Principal Components, Water Level and Air Temperature for Automatic Local Displacements (without Seasonal Effect)

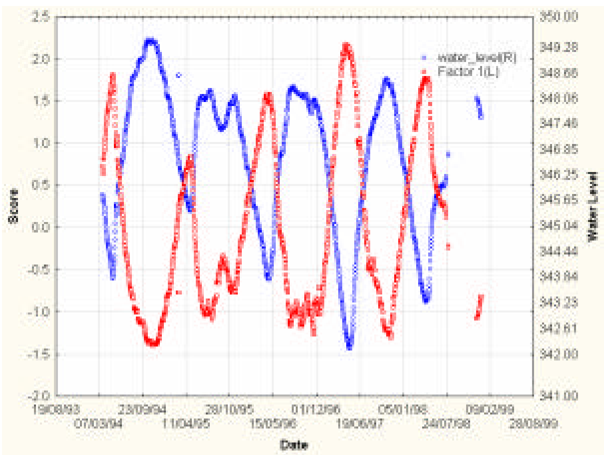


Figure 9 Scores of the First Principal Component as Function of Time.

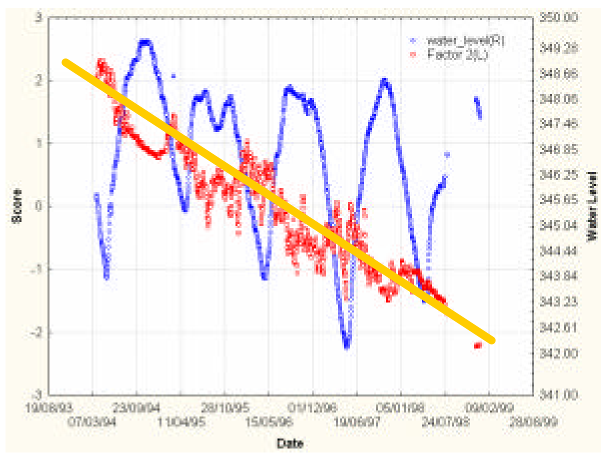


Figure 10 Scores of the Second Principal Component as Function of Time.

CONCOLUSIONS

The principal component analysis provides a method to investigate dependencies between displacements over an entire structure and to describe its global behavior with a minimal number of components. In the application of the procedure to a multiple arch dam, the first two to three principal components explain most of the variability of the original variables.

The results of the principal component analysis for the Daniel Johnson dam show that the thermal effect, the response to reservoir water level, and irreversible effects are three main components of displacements, which is consistent with the assumptions of the H-S-T model.

In our study cases, the first two principal components (explain more than 80% of the total variance) are dominated by thermal effects, while other principal components are related to reservoir water level and irreversible effects. By removing the thermal component of displacements, it becomes easier to identify the irreversible and reservoir water level effect components without the need for a priori parametric assumptions.

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