MONITORING THE CRUST MOVEMENT AT THE SALTO CAXIAS HYDROELECTRIC POWER DAMS: An Analysis of the Stability of Supporting and Controlling Points

Monitoramento de movimentos da crosta na usina hidrlétrica de Salto Caxias: análise da estabilidade dos pontos de apoio e de controle

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ABSTRACT

The Electricity Company of Paraná State-Brazil has built several hydroelectric power dams along the Iguaçu River. The last one was Salto Caxias dam, a 67 concrete unit meter high with 131 square kilometers of flooded area corresponding to $3.6x10^9$ m^3 water volume. 87 points were established around the flooded area, aiming at monitoring the crust movement of the area. Due to the fact that most of the points are located near the reservoir, where deformations might happen, 13 points were located at the farthest possible position from the reservoir. They were used as reference points for monitoring the others. This work presents the methodology applied to the analysis of the stability of the reference points, the results and conclusions as well. Data set collected during two GPS campaigns were used to realize the investigation.

Keywords: Deformation; Stability; Monitoring.

RESUMO

A Companhia Paranaense de Energia Elétrica construiu uma série de barragens de usinas hidrelétricas ao longo do Rio Iguaçu. A última construída foi a Barragem de Salto Caxias. Sendo esta de concreto com 67m de altura, inundou uma área de 131km2, que corresponde a um volume de 3.6x109m3. 87 pontos foram

estabelecidos em torno da área inundada, com o intuito de monitorar os movimentos da crosta da região. Devido ao fato que a maioria dos pontos está localizada próximo do reservatório, onde podem ocorrer deformações, selecionou-se 13 pontos que estivessem mais afastados possíveis do reservatório. Eles foram utilizados como pontos de referencia para monitorar os outros pontos. Este trabalho apresenta a metodologia aplicada na analise da estabilidade dos pontos de referencia, onde são mostrados os resultados e conclusões obtidos. Para a realização desta pesquisa foram utilizadas o conjunto de dados obtidos durante duas campanhas GPS.
Palavras-chave: Deformação; Estabilidade; Monitoramento.

1. INTRODUCTION

1.1 Seismim Induced by Reservoirs

The formation of large reservoirs in the hydroelectric power dams may induce not only crusty deformation but also occasional seism in areas which were previously assismic.This phenomenon is known as *Induced Seismim by Reservoir* (ISR*)*. The formation of a new artificial reservoir alters static condition of rock formation from a mechanical point of view (due to its weight in water mass) and from the hydraulic viewpoint, as a consequence of fluid infiltration in the subsurface, which causes inner pression in the deep rock layers. The combination of these two actions is likely to generate seism in cases where the local conditions are suitable.

Some decades ago, it was believed that artificial reservoirs caused only small magnitude seism. However, literature has pointed out many examples of earthquakes, some catastrophic, associated with the formation of large reservoirs in the hydroeletric power dams such as Boulder dam in Colorado River in the USA (1935), Kariba dams in Zambezi River/ old Rhodesia, Monteynard dam in France (1967) and Koyna dam in India (1967) *[Gupta and Rastogi, 1976]*. All these examples are about dams whose water level is higher then 100m.

Geophysic studies undertaken in large dam areas give evidence to the correlation between the seismic frequency and water height in dams. *Rother (1968)* explains that "the activity of these artificial earthquakes becomes particularly clear when the dam depth exceeds 100m; it starts once the dam is partially full, reaches a maximum, and then appears to die out after a few years." Though other researchers refer to dams which are heigher than 100m and are potentially seismogenic (*Sohrab, 1972; Gemael and Faggion, 1966; Gagg, 1997*), *Gupta and Rastogi (1976)* mention that seisms occur in areas where dams are even smaller than 100m high. They are:

- Grandival Dam/France, highest point at 78m;
- Benmore Dam/New Zealand, highest point at 96m;
- Kamafusa Dam/Japan, highest point at 50m;
- Hsinfegkiank Dam /China, highest point at 80m.

1.2 Geodetic Monitoring in Large Dam Areas

Geodetic monitoring of crust movements represents an important point of earthquake prediction programs (*Hoffman, 1969; Gupta and Rastogi, 1976*). However, the main issue brought for questioning of these programs concerning ISR, is whether earthquakes which occur near large reservoirs are caused by fluid pression increase and/or water mass weight. According to *Sohrab (1972),* geodetic monitoring made before and after artificial reservoir filling in, may help answer this question.

This way, geodetic monitoring has been undertaken before and after artificial filling in, in many parts of the world. In Brazil, these initiatives have been applied, by means of exchange programs between the Federal University of Paraná and the Companhia Paranaense de Energia (C0PEL) which has built a hydroeletric power dam alongside the Iguacu River. Within this exchange program it was possible to undertake geodetic monitoring of crust movements at Bento Munhoz da Rocha and Salto Segredo hydroelectric power dams, where levelling data, gravity and Global Positioning System (GPS) have been used. Details can be seen in *Gemael (1983; 1993), Gagg (1997) and Gemael and Faggion (1996).*

1.2.1. Monitoring Salto Caxias Hydroelectric Power Dam

The need for monitoring project of a hydroelectric power dam area at Salto Caxias can be easily explained, as it is the largest hydroelectric power dam of Compact Concrete to Roller (CCR) in South America, the 8th largest one if we consider water volume, being the third COPEL largest hydroelectric power dam. Such characteristics make up a seismogenic process in the hydroelectric power dam, though it is just 67m high.

Thus, a project of geodetic monitoring of crust movement was started in the Salto Caxias hydroeletric power dam region of Salto Caxias, based upon two different periods of time: before and after filling up in the reservoir. The first survey campaign, before filling in the reservoir occurred in mid-August 1998, and the second one after filling in the reservoir, happened in the second half of 2002 (*Teixeira, 2005*). In both campaigns, levelling, gravity and GPS data were collected. Nevertheless, only GPS data were used in this paper.

In the studied region, a monitoring network of 87 points was implemented on the ground, forming a circle around the area to be flooded, 59 of which were used for GPS data collection. Due to the fact that most points were near the reservoir, where deformation might occur, three points were selected as the supporting points (PA), in the farthest possible position from the reservoir. Later on, another 10 points were selected as the controlling points (PC).

The main aim of this paper is to analyse the stability of the points that will be used as reference points for monitoring the region crust movement. In chapter 2, the basic concepts which are fundamental for the complete understanding of the problem will be presented. In chapter 3, the studied area will be described along with the procedures followed in field surveys, taking into account the processing and adjustment of observations. In chapter 4, statistical tests which were used in the PA and PC stability analysis will be presented. Finally, in chapter 5, we will offer some final considerations.

2. AN ANALYSIS OF THE STABILITY OF REFERENCE POINTS

In geodetic monitoring of crust movement, a group of points is established in the interested region, which may represent the region. These points are monitored in relation to other points which are placed as far as possible from the region in which the movements may occur; they are called reference points. So, to obtain the real state of crust movement or displacement from the monitored area, it is necessary that the reference points to be stable throughout the time; in other words they should not suffer any displacement. Thus, an analysis of reference point stability used in this paper will be based upon sensitivity measures which will be described next.

2.1 Sensitivity Measure

A geodetic monitoring network is characterized by a group of points, about which observations are carried out at different times, providing ways to check displacement. Thus, a geodetic analysis of displacements is based upon the evaluation of repeated observations.

For monitoring geodetic network, it should be examined if the investigated object displacement can be detected (*Moraes, 2001; Teixeira, 2005*). Thus, in a geodetic network, the sensitivity measure is a statistic test to detect diplacements with probabilities from observations at two different periods of time (*Niemeier and Holman, 1984*).

In order to do this statistical test, it is necessary to estimate displacement vector (**d**) from its respective cofactor matrix of covariance ($\mathbf{Q_d}$). These quantities are estimated by means of least square method adjustment.

2.1.1 Displacement Estimative

Displacements are estimated by Gauss – Markov methods by means of a linear mathematical model (*Chrzanowiski, et. al., 1986*):

$$\mathbf{d}_{\text{obs}} + \mathbf{V} = \mathbf{B}\,\mathbf{d}\,, \tag{2.1}$$

where $\mathbf{d}_{obs}$ represents the vector of observation differences between the analysed campaigns, **B** is the partial derivatives matrix, and **d** the estimated displacement vector.

The vector ($\mathbf{d}_{obs}$) is stated as:

$$\mathbf{d}_{obs} = \mathbf{L}_2^a - \mathbf{L}_1^a\,, \tag{2.2}$$

where $\mathbf{L}_2^a$ e $\mathbf{L}_1^a$ represent respectively adjust observations from the first and the second campaigns. Matrix (**B**) is an unitary matrix which correspond to instabilities of adjusted observations between the two campaigns. In this paper, two reference points were used for the positioning of each relative point; matrix (**B**) is defined as:

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad . \tag{2.3}$$

In the used methodology to estimate displacements, the weight matrix of the only observation $\left(\mathbf{P}_{d_{obs}}\right)$ is estimated for the function of the first and the second campaigns, and it is expressed by model (*Chrzanowiski, et. al., 1986*):

$$\mathbf{P}_{d_{obs}} = \mathbf{P}_2 - \left[\mathbf{P}_2\left(\mathbf{P}_1 + \mathbf{P}_2\right)^{-1}\mathbf{P}_2\right] = \mathbf{P}_1\left(\mathbf{P}_1 + \mathbf{P}_2\right)^{-1}\mathbf{P}_2 = \left(\mathbf{P}_1^{-1} + \mathbf{P}_2^{-1}\right)^{-1} \quad . \tag{2.4}$$

where $\mathbf{P_1}$ and $\mathbf{P_2}$ represent, the weight matrices which refer to the first and second campaigns .

From these data, displacements can be estimated by using the following expression:

$$\mathbf{d} = \left(\mathbf{B}^T\mathbf{P}_{d_{obs}}\mathbf{B}\right)^{-1}\mathbf{B}^T\mathbf{P}_{d_{obs}}\mathbf{d}_{obs} \quad . \tag{2.5}$$

The variance-covariance matrices $\left(\sum \mathbf{d}\right)$ and the covariance cofactor $\left(\mathbf{Q_d}\right)$ from displacementss are estimated respectively by:

$$\sum \mathbf{d} = \bar{\sigma}_0^2\left(\mathbf{B}^T\mathbf{P}_{d_{obs}}\mathbf{B}\right)^{-1} \text{ , and} \tag{2.6}$$

$$\mathbf{Q_d} = \left(\mathbf{B}^T\mathbf{P}_{d_{obs}}\mathbf{B}\right)^{-1}, \tag{2.7}$$

where $\overline{\sigma}_o^2$ is *a posteriori* variance which is calculated by:

$$\overline{\sigma}_0^2 = \frac{\nu_1 \hat{\sigma}_{0_1}^2 + \nu_2 \hat{\sigma}_{0_2}^2}{\nu_1 + \nu_2} \ . \tag{2.8}$$

in which ν_1 and $\nu_2, \hat{\sigma}_{0_1}^2$ and $\hat{\sigma}_{0_2}^2$ represent, respectively, degrees of freedom and *a posteriori* variances which refer to the first and the second campaigns:

2.1.2 Sensitivity Test

The existence of meaningful displacement between the two campaigns, require the formulation of null and alternative hypotheses:

$$H_{oi} : E\{d_i\} = 0 \ , \qquad (i = 1, ..., u) \tag{2.9}$$

$$H_A : E\{d\} \neq 0 \ . \tag{2.10}$$

Statistics used for testing the null hypothesis is based upon Snedecor central F distribution (*Pelzer*, *1971*), and it is represented by the following expression:

$$F_{0\,i} = \frac{d_i^2}{\left[\left(q_{d_i}\right)\left(\overline{\sigma}_0^2\right)\right]} \ , \qquad (i = 1, ..., u) \tag{2.11}$$

where d_i^2 and q_{d_i} represent, respectively, the i-th displacement of **d** vector and its respective covariance cofactor.

This way, the statistics of each displacement contained in **d** vector is calculated by means of equation (2.11)

The null hypothesis is valid if, and only if:

$$F_{0_i} < F_{m_{d_i}, \nu_1 + \nu_2, \alpha} \ , \tag{2.12}$$

where m_{di} is the dimension of the vector which corresponds to this displacement.

As it can be observed by means of equation (2.11), this test is done in a discrete way, that is to say, for each one of the displacements contained in vector **d**. This way, the analysed point will be considered stable (no displacement), to a confidence level, if and only if all vector displacements follow condition (2.12).

If one or more displacements of vector **d** did not follow the condition (2.12), the point would be considered unstable and the alternative hypothesis (H_A) would be considered valid. Statistics associated with the alternative hypothesis is distributed at F non-central and based on the parameter square of non-centrality (δ_0^2), which can be found in Table 1 (*Kuang, 1996*).

Table 1 – Non centrality parameter at power of the test and at the significance level.

Power of the Test (1- β_0)	**Significance Level(α_0)**			
	α_0= 0,01%	**α_0= 0,10%**	**α_0= 1%**	**α_0= 5%**
50%	3,72	3,29	2,58	1,96
70%	4,41	3,82	3,10	2,48
80%	4,73	4,13	3,42	2,80
90%	5,17	4,57	3,86	3,24
95%	5,54	4,94	4,22	3,61
99%	6,22	5,62	4,90	4,29
99,90%	6,98	6,38	5,67	5,05

The alternative hypothesis is tested by means of the following expression:

$$F_A = \frac{\mathbf{d}^T \mathbf{Q}_\mathbf{d}^{-1} \mathbf{d}}{\overline{\sigma}_0^2} \quad . \tag{2.13}$$

By calculating statistics associated with the alternative hypothesis, vector **d** will be determined if and only if:

$$F_A > \delta_0^2 \, . \tag{2.14}$$

The sensitivity criterion for monitoring geodetic networks can be determined by spectral resolution of matrix $\mathbf{Q_d}$, as follows:

$$(\mathbf{Q_d} - \lambda \mathbf{I})\mathbf{M} = 0 \ , \tag{2.15}$$

which will turn into

$$\sum \mathbf{Q_d} = \begin{bmatrix} m_1 & m_2 & \dots & m_u \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \end{bmatrix} \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda u \end{bmatrix} \begin{bmatrix} m_1 & \dots & \dots & \dots \\ m_2 & \dots & \dots & \dots \\ m_3 & \dots & \dots & \dots \\ m_u & \dots & \dots & \dots \end{bmatrix} \tag{2.16}$$

in which λ_i is the eigenvalue in matrix $\mathbf{Q_d}$, and $\mathbf{m_i}$ is its correponding eigenvector.

By admitting that λ_i $(i = 1, 2, ..., \mathrm{u})$ eigenvalues are in a decrescent sequence, with $\lambda_1 = \lambda_{máx.}$ and $\lambda_\mathrm{u} = \lambda_{\min.}$, the corresponding eigenvector to λ_1 and λ_u are $\mathbf{m}_1$ and $\mathbf{m}_\mathrm{u}$, respectively. This way, the sensitivity equation or minimum displacement detected is expressed by:

$$d_{mín.} = \overline{\sigma}_o \delta_o \sqrt{\lambda_1}\, \mathbf{m}_1 \,. \qquad (2.17)$$

3. STUDY AREA AND FIELD SURVEY

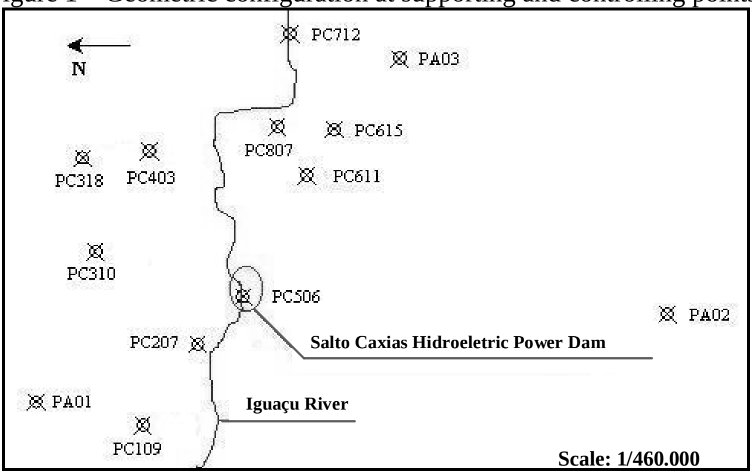
3.1 Salto Caxias Hydroelectric Power Dam

As it was mentioned previously, Salto Caxias Hydroelectric power dam is one of the most important COPEL dams, being the third biggest one, and it is only smaller than Foz do Areia and Salto Segredo . It is 67 meters high and 1,083 meters long besides being CCR gravity type (compact concrete to roller). Its reservoir stretches along 131 km^2 surface and its dammed water volume is 3,6 x 10 m^3.

3.2 Supporting, Controlling and RRNN Points

At first, 97 points for monitoring Salto Caxias hydroelectric power dam were designed, 4 out of the 97 points would be selected for suiting PA goals, and 10 others were selected as PC. However, just 87 points were implemented out of that quantity, and only 3 PA and 10 PC were selected, according to the original project. Figure 3.1 shows geometrical configuration at Supporting and Controlling points.

Figure 1 – Geometric configuration at supporting and controlling points.



In order to implement the above points, the same technical specifications from the ones in the project of geodetic auscultation were used from Bento Munhoz da Rocha Hydroelectric power dam area, (*Gemael and Doubeck*, *1982*). The points were spread out along 1 km under the surface and about 20 cm above it.

3.3. Field Survey and Data Processing

Two GPS campaigns were undertaken: the first one lasted from the 5th to the 10th of October 1998, before filling up the reservoir, while the second lasted from the 16th to the 20th of December 2002. The reservoir filling up occurred from November to December 1998. To undertake the two campaigns, there were 4 ASHTECH Z-XII receivers and 1 TRIMBLE SSI receiver.

Points PA01, PA02, and PA03 were positioned in relation to PARA and UEPP points, which belong to Brazilian Network of Continuous Monitoring (RBMC). These two points belong to the Network of Geocentric Reference System for the Americas (SIRGAS). SIRGAS coordinates refer to ITRF-94, time 1995.4.

The three PA were tracked by using the static relative positioning, which lasted for 6 hours. A sample rate data collection of 15 seconds was used, at 10 degree elevation angle so as to minimize degradations which came from troposphere and from multipath effect. Table 2 shows baseline lengths among RBMC and PA points.

Table 2 – Baseline length formed at the first campaign.

BASELINE	LENGTH (km)
PARA-PA01	436,30
PARA-PA02	432,20
PARA-PA03	414,10
UEPP-PA01	425,40
UEPP-PA02	459,00
UEPP-PA03	435,70

Ten PCs were tracked by means of relative static positioning method and the data collection lasted for 3 hours with a sampling rate of 15 seconds. The PCs points were positioned in relation to the PAs. Table 3 presents the baseline length formed among the PAs and PCs in the first and second campaigns.

Table 3 – Baseline length formed at the first campaign.

BASELINE	LENGTH (km)	BASELINE	LENGTH (km)
PA01-PC109	7,20	PA02- PC611	24,4
PA01-PC207	11,30	PA02- PC506	28,0
PA01-PC310	10,60	PA03- PC109	29,60

PA01-PC318	16,40	PA03- PC207	23,10
PA01-PC403	18,70	PA03- PC310	23,80
PA01-PC506	15,30	PA03- PC318	21,90
PA01-PC611	23,30	PA03- PC403	18,00
PA01-PC615	26,70	PA03- PC615	6,50
PA01-PC712	30,90	PA03- PC712	8,60
PA01-PC807	24,20	PA03- PC807	9,20

3.4 Processing and Adjusting the GPS Observations

GPS observations were processed and adjusted with by using BERNESE scientific software, version 4.2. The ambiguities related to the baseline points PC403 and PC712 referring to the first and second campaigns were neither solved nor fixed. The other points had their ambiguities not fixed.

A posteriori variances from all relative points refering to the first and second campaigns are shown in Table 4.

Table 4 – A *posteriori* variances from all relative point involved in adjustments from the first and second campaigns.

RELATIVES POINTS	***A POSTERIORI* VARIANCE**	
	1st CAMPAIGN	**2nd CAMPAIGN**
PA01	1,4	1,6
PA02	1,9	2,3
PA03	2,1	1,8
PC109	1,6	1,9
PC207	1,6	1,8
PC310	1,5	2,6
PC318	2,1	1,8
PC506	1,9	1,8
PC611	1,5	2,1
PC615	1,6	1,8
PC807	1,6	2,2

Geocentric cartesian coordinates adjusted from PAs and PCs with their respective standard deviation, and *a posteriori* variances which refer to the first and second campaigns will be used in the following chapter for analysing their respective stability.

4. PA AND PC STABILITY ANALYSIS

As it was described in chapter 2, an analysis of reference points starts with the estimate of their displacements, whose methodology is based upon least square adjustment. Thus, by using equations (2.5.) and (2.6), PA and PC displacements were estimated, regarding X, Y, Z and their variance-covariance. Table 5 shows estimated displacements and their standard deviation.

Table 5 –Eestimated displacements and their respective Standard deviation.

POINTS	**1ª / 2ª CAMPAIGN**					
	X (m)	**Y (m)**	**Z (m)**	**σ_x (m)**	**σ_Y (m)**	**σ_z (m)**
PA01	-0,0126	0,0237	0,0042	0,0059	0,0072	0,0054
PA02	-0,0105	0,0250	0,0228	0,0083	0,0097	0,0093
PA03	-0,0044	0,0044	0,0028	0,0066	0,0075	0,0067
PC109	0,0223	0,0029	-0,0015	0,0056	0,0055	0,0047
PC207	0,0069	0,0072	-0,0080	0,0066	0,0065	0,0069
PC310	0,0733	-0,0687	-0,0558	0,0040	0,0008	0,0050
PC318	0,0002	0,0081	0,0004	0,0054	0,0061	0,0063
PC506	-0,0119	-0,0172	0,0064	0,0064	0,0066	0,0059
PC611	-0,0089	0,0072	0,0070	0,0064	0,0063	0,0061
PC615	-0,0273	0,0158	0,0043	0,0022	0,0058	0,0058
PC807	-0,0099	-0,0046	-0,0049	0,0059	0,0054	0,0061

By means of Table 5, displacements were noticed in the centimeter and millimeter levels, except for the displacement of component (Z) at point PC318, which reached sub-millimetric order (0,0004). The largest displacements were the ones which occurred at point PC310 (X,Y,Z) while the smallest ones occurred at points PA03(X) and PC109 (Y,Z). It was also noticed that the displacement accuracy was at millimeter and sub-millimeter level.

The displacements were statistically tested by means of sensitivity test and according to what is described at section 2.1.2. The goal was to check displacement meaning. To achieve these goals, later *a posteriori* variances were calculated by means of equation (2.8). These numbers are indicated in Table 6.

Table 6 – A *posteriori* variance, the only one at different Period of times.

POINTS	$\bar{\sigma}_0^2$	**POINTS**	$\bar{\sigma}_0^2$
PA01	1,50	PC318	1,95
PA02	2,10	PC506	1,85
PA03	1,95	PC611	1,80
PC109	1,75	PC615	1,70
PC207	1,70	PC807	1,90
PC310	2,05		

This test is started by calculating statistics (F_{0_i}), associated with the null hypothesis (H_{oi}) which is performed in a discrete way, in other words, for each one of these displacements which are part of vector **d** (Table 5). Table 7 shows this test result and its respective decision concerning each point stability.

Table 7 – Sensitivity test results and the decisions concerning point stabiblity.

POINTS	NULL HYPOTHESIS (F_{0i})			F (α=1%) ($\nu_1 + \nu_2$= 6) m_i=1 CONDITION: F_{0i} < F (1, 6, 1)= 13,74			DECISIONS CONCERNING POINT STABIBLITY
	X	Y	Z	X	Y	Z	
PA01	4,48	10,97	0,61	ACCEPT	ACCEPT	ACCEPT	STABLE
PA02	1,60	6,67	5,96	ACCEPT	ACCEPT	ACCEPT	STABLE
PA03	0,44	0,34	0,17	ACCEPT	ACCEPT	ACCEPT	STABLE
PC109	15,96	0,27	0,06	REJECT	ACCEPT	ACCEPT	UNSTABLE
PC207	1,09	1,22	1,35	ACCEPT	ACCEPT	ACCEPT	STABLE
PC310	338,82	8098,91	61,32	REJECT	REJECT	REJECT	UNSTABLE
PC318	0,001	1,76	0,004	ACCEPT	ACCEPT	ACCEPT	STABLE
PC506	3,42	6,69	1,16	ACCEPT	ACCEPT	ACCEPT	STABLE
PC611	1,92	1,29	1,32	ACCEPT	ACCEPT	ACCEPT	STABLE
PC615	154,61	7,39	0,55	REJECT	ACCEPT	ACCEPT	UNSTABLE
PC807	2,84	0,72	0,65	ACCEPT	ACCEPT	ACCEPT	STABLE

By means of Table 7 it is noticed that the sensitivity test detected meaningful displacements in three points, and that the highest statistical data were from point PC310 where the largest displacements occurred (see Table 5). This way, as these points were statistically unstable, the alternative hypothesis is valid (H_A), and its statistics follows F non-central distribution. The alternative hypothesis aims at testing whether or not displacement vector (**d**) can be detected at a confidence level $(1-\alpha_0)$ and at test power $(1-\beta_0)$. Table 8 shows this test result for each one of the three points which were considered unstable by the null hypothesis.

Table 8 – Alternative hypothesis statistics.

POINTS	F_A	(α_0= 5% , β_0= 20%) Condition: $F_A > \delta_0^2 = 7{,}84$
PC109	11,66	ACCEPT
PC310	495,45	ACCEPT
PC615	61,33	ACCEPT

By means of Table 8, one may notice that all kinds of statistics follow the condition determined by the altenative hypothesis, what means that the vector of all displacements can be detected. The obedience to this condition confirms how meaningful these displacements are at confidence level $(1-\alpha_0)$ and test power $(1-\beta_0)$.

Concerning the statistics of both the null hypothesis and the alternative one, it is noticed that the first one is done discretely, i.e., the displacement at each component (X, Y, Z) is tested separately, while in the second one, displacements at each point are tested as a whole.

It was noticed that the statistical values vary according to the magnitude displacements. For example, point PA03 has got relatively small displacements (Table 5). Statistics from this point followed the condition determined by the null hypothesis with small values (Table 7). On the other hand, at point PC310 which has the smallest displacements, these statistics are very high (Tables 7 and 8)

After statistically confirming the meaning of these displacements, their respective sensitivities were calculated by means of equation (2.17), which produces statistically the minimum values of each estimated displacement. By means of these values, the meaning of these displacements can be checked physically. These positive values can be observed in Table 9.

Table 9 – Minimum displacements which can be detected.

POINTS	**$\alpha_0 = 5\%; 1-\beta_0 = 80\% \Rightarrow \delta_0 = 2,80$**		
	X (m)	**Y (m)**	**Z (m)**
PC109	0,0194	0,0130	0,0139
PC310	0,0145	0,0006	0,0030
PC615	0,0053	0,0198	0,0024

Table 9 shows how meaningful estimated displacements are (Table 5). It was noticed that the differences among the estimated displacements and minimum displacements which can be detected are very high. The largest differences were at point PC310 (X,Y,Z).

By correlating Tables 5, 7 and 9, one may notice that all estimated displacements, with their values higher than their detected minimum displacements, were rejected at the sensitivity test – the null hypothesis.

5. FINAL CONSIDERATIONS

This paper aimed at analysing PA and PC stability which were used as reference points for monitoring crust movement at Salto Caxias hydroelectric power dam. This goal was achieved by means of two GPS survey campaigns which were undertaken at those points.

The coordinate standard deviations of processed baseline data were satisfactory at both campaigns. This is related to tracking time at each point, and the strategies adopted in data processing. However, a precision reduction of most coordinates at the second campaign in relation to the first campaign was noticed, in spite of the fact that the same procedures and equipment were used in both campaigns. Concerning the statistics used in displacement analysis, the sensitivity test was proved to be effective. There were displacements in all 11 analyzed points. Meaningful displacements were detected in three points, which were considered statistically unstable. At another eight points, displacements were not meaningful, but statistically stable. It has to be pointed out how important the sensitivity test was, as these points would have been considered unstable if this test had not been applied.

The logistics involved (time available, human and financial resources) in GPS survey campaigns was highly important. Due to the logistics, it was not allowed to track PA first and right after do the processing and adjustment of observations, plus the statistic analysis of displacements, for later on tracking the PC, undertaking the same procedures for the PC, and finally tracking the left points implemented at the referred region.

The PA and PC were carefully selected, aiming at the stability throughout the experiment time, for they served as base point (reference base), in monitoring crust movements in the region. However, displacements were too high in some points, as for instance, at point PC310. This way, only by means of a highly deeper study involving other geodetic techniques (geometric levelling, gravity and so on, and so forth) and other knowledge areas, such as geology, one may assert that those displacements were due to a dam construction followed by the reservoir filling up.

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