STAGE 1 OF SUBSIDENCE MONITORING OF THE AREA SURROUNDING SALTO CAXIAS POWER DAM, IN BRAZIL

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Abstract

The Electricity Company of Paraná, has built a series of hydroelectric power dams along the Iguaçu River, located in Southern Brazil. The last one is the Salto Caxias Power Dam. This is a concrete dam, 67 meters high. The filling of this dam is expected to flood an area equal to 141 km^2, corresponding to a volume of 3.6×10^9 m^3. Before the closing of the dam itself, a monitoring network of as many as 100 points was implement on the ground, encircling the area to be flooded. Additional control points external do this area were also implemented. The objective of the network is to determine the subsidence of the surrounding area. Gravimeter, geodetic levelling and GPS occupied the points of both networks in a first field campaign, which took place during 1998. A new field campaign will be carried out some time after the reservoir reaches its peak. This paper describes the design and implementation of the network and some characteristics of the fieldwork. Emphasis is given to the processing and analysis of the GPS collected data.

1. Introduction

It has been long known that reservoir-induced deformations due to accumulation of a large mass of water following the construction of large dams are potentially seismogenic [Rothe, 1968; Sohrab, 1972]. To monitor such deformations, arrays of points surrounding a particular dam and neighbouring area are established. These points have their coordinates or other type of pertinent geodetic information determined by geodetic techniques, either classical or space-based (or both), at particular epochs or continuously. By comparing the resulting displacements derived from coordinate differences (properly made compatible in time) a deformation pattern can be derived and used to feed a deformation model. There are several examples of such approach found elsewhere in the literature [e.g., Nakiboglu and Lambeck, 1982; Lambert et al., 1986; Dixon et al., 1997; Bitelli et al. 2000; Chang, 2000; Kaufmann and Amelung, 2000; Wang, 2000]

The Electric Company of the State of Paraná (COPEL), Brazil, has built a series of hydroelectric power dams along the Iguaçu River. This river stretches in the East-West direction, being a tributary of the Paraná River. The famous Iguaçu Falls are located in the Iguaçu River, close to its encounter with the Paraná River. The largest power dams built are the Bento Munhoz da Rocha Dam, the Segredo Dam and, most recently, the Salto Caxias Dam. The Federal University of Paraná (UFPR) has worked with COPEL, in the terms of an agreement of co-operation, in the monitoring of local subsidence provoked by the load created by the filling of the dam reservoir. For this investigation, geodetic levelling, gravimetry, and, more recently, GPS data has been used. Gemael [1983; 1993] presented the results related to the Bento Munhoz da Rocha Dam, based on height differences resulting from geodetic levelling before and after the filling of the reservoir. Gagg [1997] carried out an investigation based on the gravimetric data available using statistical tests as a tool in an attempt to see the subsidence signal. Gemael and Faggion [1996] described the results related to the Segredo Dam, based again on the height differences from geodetic levelling.

This paper deals with stage 1 of the subsidence monitoring of the area surrounding Salto Caxias Dam. By stage 1 we mean the network design, monumentation and first field campaign. It contains a description of the characteristics of the dam itself and of the first field campaign carried out on the monuments established surrounding the dam and its reservoir, with focus on the GPS campaign. An analysis of the GPS data processing and results is included.

2. The Salto Caxias Dam Project Design

The Salto Caxias Dam, and its reservoir, is located in the Southwest portion of the State of Paraná in Brazil, as schematically indicated in Figure 1, close to the borders with Paraguay and Argentina. It is a concrete dam, 67 meters high. Its installed power equals to 1240 MW. The filling of this dam is predicted to flood an area equal to 141 km^2, corresponding to a water volume of 3.6×10^9 m^3. This dam is the last one of a series of dams built by COPEL along the Iguaçu River. Its construction took several years and was finalized at the end of 1998, when the dam was closed. Figure 2 shows a picture of the dam's main structure. Figure 3 shows a view of the Iguaçu River before arriving at the dam. Most of the area shown in this figure is within the flooding zone.

A project was designed in order to monitor eventual subsidence provoked by the reservoir's water load by means of repetitive surveys, carried out in different times, aimed at determining height differences, coordinate differences and gravimetric anomalies. The idea is to determine a subsidence signal independently from each one of those informations.

The deformation and change in the in-situ state of stress induced by reservoir may create seismogenic conditions. The investigation of the new stress distribution and location of potential critical concentration of stresses is of a particular interest. The change of in-situ stresses can be modelled using finite element method (FEM) which includes geometry, loading conditions from the weight of reservoir, tectonic conditions, and geology (Szostak-Chrzanowski et al., 1993). Another aspect of effects of reservoir loading is change in gravity field and deflection of vertical. A method for a simultaneous analysis of deformations and gravity changes has been developed at the University of New Brunswick. (Szostak-Chrzanowski et al., 1995). Integration of the measured displacements and measured gravity changes with the FEM model will enhance the understanding of the reservoir effect.

A network of points was implemented along the existing roads in the area in such a way to surround both the dam and the area to be flooded. A total of 97 bench mark (BM) monuments were materialized, covering a length of approximately 100 km. The location of some of the monuments was selected in such a way that they can be later used for controlling the deformations of the dam's structure and for study on the silting up of the reservoir's bottom.

Each one of those BMs were occupied by geodetic levelling, gravimetry and GPS during the first campaign which took place during 1998 before the closing of the dam. Subsequent campaigns are going to take place after the total filling up of the reservoir. For the gravimetric survey two LaCoste-Romberg model G gravimeters were used. For the geodetic levelling, precision levels Wild-N3 were used. For the GPS campaign, three receivers were used: two Ashtech Z-12 and one Trimble 4000 SSE. All equipments used in this campaign belong to UFPR.

The design of the GPS component followed additional guidelines. Because most of the BMs are located inside the area in which subsidence is expected, additional three points were implemented farther away. It is our expectation that they are not going to move as a consequence of the loading. To guarantee further control, these three new points (called in the project as "support points" or PA) were connected to the Brazilian Network for Continuous Monitoring of GPS (RBMC). The three PA points were used to form shorter baselines with a number of selected BMs. Not all BMs could be connected to the PA due to time constraints. The BMs, which were connected to the PA points, were called in the project as "control points" or PC. They were 10 in total. All PA and PC points were determined with conventional static relative positioning. All the other BMs had their coordinates determined from the PC points using the rapid static method. Figure 4 presents the scheme used for the GPS component. It shows the location of the three PA points (PA01, PA02 and PA03) and the 10 PC points (P109, P207, P310, P318, P403, P506, P611, P615, P712 and P807) disposed around the Iguaçu River. The flooding area is indicated as well as the location of the dam and the several small communities in the surroundings. All BMs are located along the roads in the vicinity of the dam.

Figure 1 – Location of the Salto Caxias Power Dam.

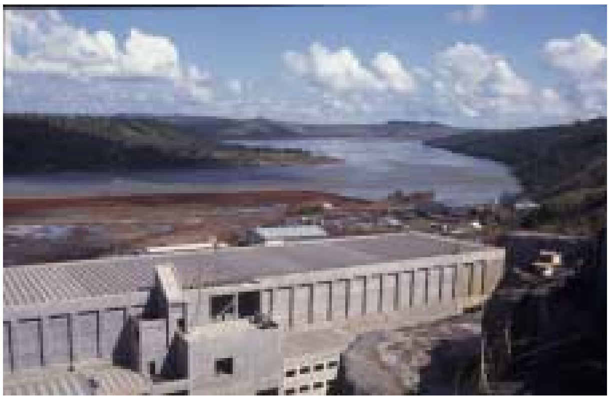

Figure 2 – The dam’s main structure.

Figure 3 – View of the Iguaçu River before arriving at the dam.

3. Collection, processing and analysis of the GPS data

The GPS data was collected between August 5 (DOY 217) and August 10 (DOY 222), 1998. The first four days were dedicated to the occupation of all PA and PC points. These points were occupied in such a way that each one of them would have been visited at least two times, allowing each one of them to be involved in a minimum of four sessions. As far as the PA points are concerned, PA01 was occupied in four days whereas PA02 and PA03 were visited in two days (unfortunately, one day worth of data for PA02 was lost). These PA points were connected to the RBMC stations PARA and UEPP. The session length varied between 7 and 9 hours (exception for baseline UEPP-PA01 occupied for only 4 hours on DOY 218) with a sampling rate of 15 seconds. Figures 5 and 6 show PA points PA01 and PA03. Point PA01 is located in a square, opposite from one of the localities City Hall. Point PA03 is one of the BMs located in another locality (the typical morning fog can be noted). Concerning the PC points, they were all occupied forming 3 hours long sessions (exception for baseline PA01-P109 occupied for only 1 hour on DOY 219) with the same sampling rate of 15 seconds. Table 1 presents the baseline length of all baselines formed among the RBMC stations, PA and PC points. The last two days were dedicated to the determination of the remnant BMs, which were occupied in the rapid static mode, forming 15 minutes long sessions with the PC points, with a 5 seconds sampling rate.

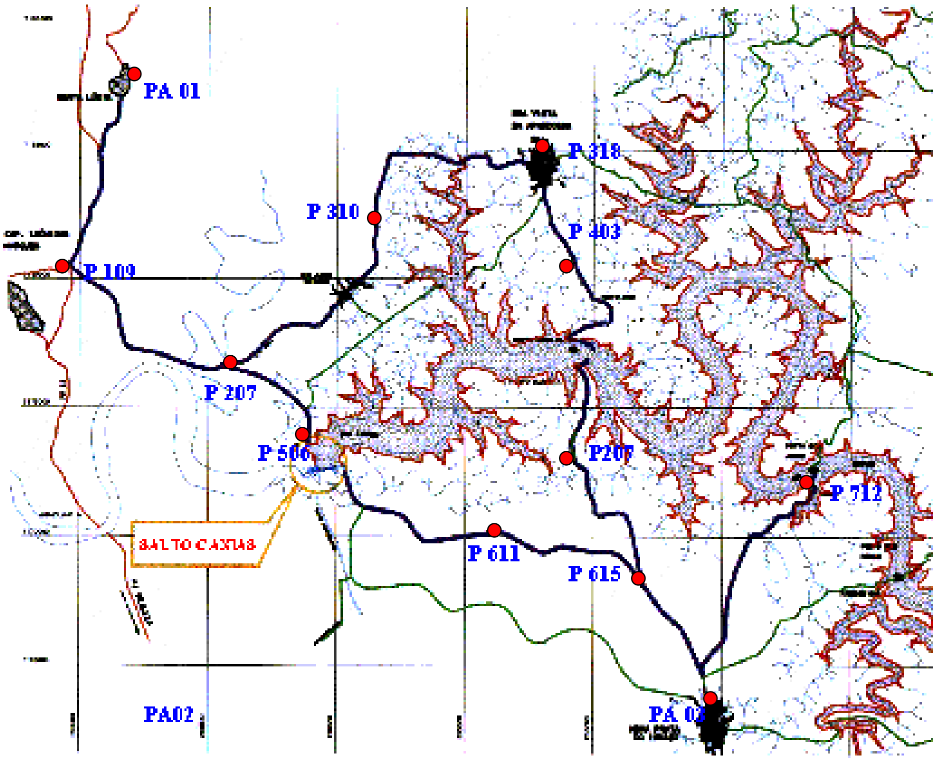

Figure 4 – Schematic distribution of PA and PC points surrounding the Iguaçu River.

Baseline	Baseline Length (km)	Baseline	Baseline Length (km)
PARA - PA01	436.3	PA01 - P615	26.7
PARA - PA02	432.2	PA02 - P712	32.7
PARA - PA03	414.1	PA02 - P611	25.4
UEPP - PA01	425.4	PA02 - P506	28.0
UEPP - PA02	459.0	PA02 - P807	28.5
UEPP - PA03	435.7	PA03 - P207	23.1
PA01 - P207	11.3	PA03 - P403	18.0
PA01 - P403	18.7	PA03 - P712	8.6
PA01 - P712	30.9	PA03 - P611	9.8
PA01 - P611	23.3	PA03 - P506	18.8
PA01 - P506	15.3	PA03 - P109	29.6
PA01 - P109	7.2	PA03 - P318	21.9
PA01 - P318	16.4	PA03 - P807	9.2
PA01 - P807	24.2	PA03 -P310	23.8
PA01 - P310	10.6	PA03 - P615	6.5

Table 1 – Length of the baselines formed between the RBMC stations, PA and PC points.

Figure 5 – Point PA01

Figure 6 – Point PA03

The GPS data collected at the PA and PC points were processed using the University of New Brunswick's DIPOP software suite. The RBMC coordinates of stations PARA and UEPP are given in SIRGAS values attached to epoch 1995.4. To these coordinates rotations were applied given by the NNR-NUVEL1 model (De Mets et al., 1994) to make the whole processing attached to epoch 1998.6, the middle to the campaign. IGS precise ephemerides were used. Troposphere was modelled using a combination of Saastamoinen tropospheric model and Ifadis mapping function. A number of 4 residual tropospheric delay parameters were adjusted in each one of the sessions. For the processing of the longer baselines ionospheric-delay free observables were formed. For the shorter baselines, an attempt was made to resolve the ambiguities. The a priori standard deviations for the observations were given values between 6 and 12 cm. Each one of the baselines was computed independently and later on in a network mode (disregarding correlation among simultaneously observed sessions). For the network solution the PA points formed a network with the RBMC stations, being the coordinates of the latter stations constrained to the computed 1998.6 values. The PC points formed another network attached to the PA points, using their coordinates as originated from the first adjustment.

In an attempt to gain an appreciation on the precision of the results an analysis based on the standard deviation obtained from the network adjustment follows. Figure 7 shows the standard deviation as obtained by the network adjustment. Let's us just make clear that even though all points are represented together in the same figure, they come from different network solutions. Because the correlations between common baselines were disregarded in the network solution, these values may be a little optimistic. If we concentrate our analysis on the height component, which provides a very important information since the main interest is on subsidence monitoring, we may say that the higher values encountered for this component may suggest that a larger number of tropospheric parameters should be estimated.

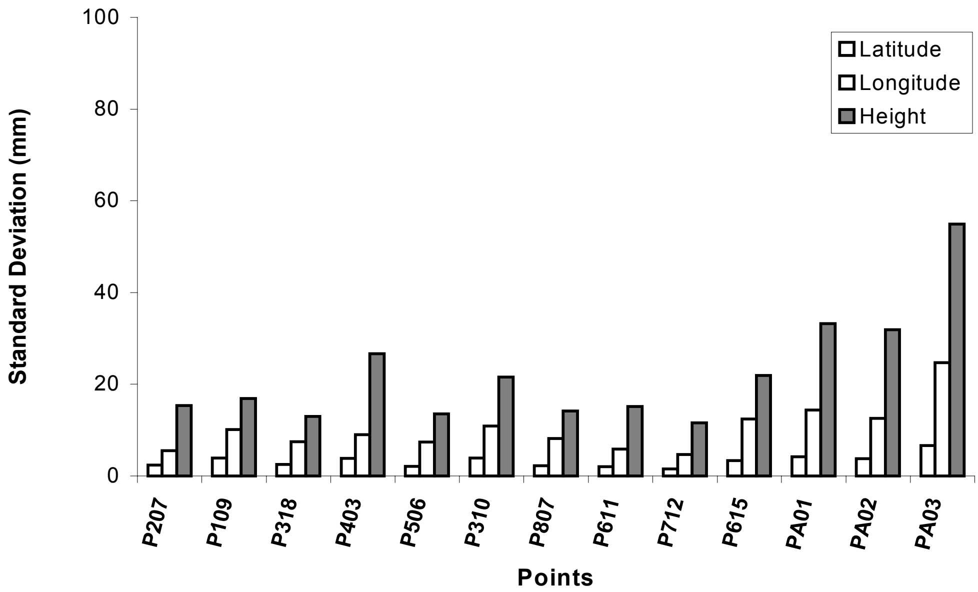

Figure 7 – Formal error as given by the network adjustment.

4. Conclusions

This paper described the stage 1 of the project for subsidence monitoring at the site of Salto Caxias Power Dam. Emphasis was given to the GPS component of the project and only results coming from this component were presented. It can be seen that the support and control points have most of their horizontal components determined at the centimetre level. Higher values were found for the height, which may suggest that the troposphere should be better dealt with. More investigation is on its way to improve these results.

The processing of the GPS rapid static data has been done using Trimble Geomatics Office but the results are not considered here. The same happened with the gravimetric and geodetic height data.

A new campaign, the stage 2 of the project, is currently under way with the re-levelling of the BMs. Gravimetric and GPS survey will follow. The deterministic modelling may be performed at the stage 3 of the project.

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