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Factors that influence the geodetic monitoring of dams using total station

Fatores que influenciam no monitoramento geodésico de barragens utilizando estação total

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Abstract: This paper analyzes the influence of external agents during the geodetic monitoring of structures, a case study at the dam of the Hydroelectric Power Plant (UHE) in Mauá-PR, combining the satellite positioning method using GNSS with the irradiation method using robotic Total Station for determine eventual movements of monitoring points embedded in the dam parameter downstream and in the crest of the upstream bus. The procedures adopted consist of comparing the results of the monitoring carried out with the spillway gates opened with the results of the same monitoring carried out with the spillway gates closed and, consequently, analyzing whether the opening of the spillway interferes with the geodetic monitoring since, the spillway located in the center of the dam. Parallel to this, with the same equipment, the monitoring of points embedded in the crest of the upstream dam was carried out from two pillars, one on the left bank, another on the right bank of the reservoir and two systems of forced centering on the dam. After processing the data, analyzes were made where it was found that the fact that the dam has an open spillway affects the determination of the coordinates in the body of the dam downstream, presenting values significantly different from the coordinates with the open or closed spillway. It was also observed that depending on the point of the geodetic network used to determine the coordinates of the points on the crest of the dam, right, left margin or on the dam the coordinates also show significant variations.

Keywords: Geodetic monitoring; Monitoring of dams; Total Station.

Resumo: Este artigo analisa a influência de agentes externos durante o monitoramento geodésico de estruturas, estudo de caso na barragem da Usina Hidrelétrica (UHE) de Mauá-PR, combinando o método de posicionamento por satélite utilizando GNSS com o método da irradiação utilizando Estação Total robotizada para determinar eventuais movimentos de pontos de monitoramento da barragem. Os procedimentos adotados consistem em comparar os resultados do monitoramento realizado com as comportas do vertedor abertas com os resultados do mesmo monitoramento realizado com as comportas do vertedor fechadas e, consequentemente, analisar se a abertura do vertedor interfere na precisão do monitoramento geodésico, uma vez que o vertedor se localiza no centro da barragem. Após o processamento dos dados foram feitas análises onde verificou-se que o fato da barragem estar com o vertedor aberto, afeta a precisão das coordenadas no corpo da barragem à jusante apresentando valores significativamente diferentes das coordenadas com o vertedor aberto ou fechado. Paralelamente, com o mesmo equipamento, realizou-se o monitoramento de pontos engastados na crista da barragem à montante onde observou-se que dependendo do ponto da rede geodésica utilizado para a determinação das coordenadas dos pontos na crista da barragem, margem direita, esquerda ou sobre a barragem as coordenadas também apresentam variações significativas.

Palavras-Chave: Monitoramento Geodésico; Monitoramento de Barragens; Estação Total.

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1. Introduction

To guarantee the necessary safety conditions for dams throughout their useful life, prevention and control measures must be adopted. These measures ensure a reduced or practically nil probability of an accident occurring. However, they must be periodically reviewed taking into account any changes resulting from aging and deterioration of structures (ANA, 2018).

In order to establish control over the use and safety of the dam, several procedures are necessary aimed at the management and control of the dam system so that new disasters are avoided. Continuous monitoring aimed at the safety and integrity of its structure using geodetic measurements have been efficient for control.

Monitoring a structure from the point of view of geodetic positioning means determining and comparing the coordinates of monitoring points at two different times, checking and analyzing whether there were variations, within a level of significance, in these coordinates (SILVEIRA, 2006).

The first dam monitoring record was in Cantaria of Grosbois, France. In 1853, geodetic measurements were taken on this dam to observe crest displacements. This dam had presented numerous problems since the beginning of filling the reservoir in 1838 and had to be reinforced on more than one occasion. Thus, from 1853, geodetic measurements became common practice in dams (SILVEIRA, 2006; DA CRUZ, 2015; JERKE, 2019).

In the academic sphere, the number of works related to the monitoring of large anthropic structures (man-made) has increased in recent years.

In China, Jingzhan (2002) compared the result of deformation monitoring of the HPP Ertan dam between the TCA2003 Total Station, T3000 Electronic Weiwei and DI2002 Range Finder, all with the same precision in the same work content, in the same observation plane, in the same observation period and carried out under the same conditions as the test area. Jingzhan (2002) concluded that the observations of the TCA2003, T3000 and DI2002 Total Station are very different in terms of observation efficiency, indicating that the TCA2003 total station is significantly better than other instruments with the same precision.

At the University of New Brunswick - Canada, Chrzanowski and Szostak-Chrzanowski (2009) conducted a study on old problems and new solutions in monitoring structures, concluding that the effects of modifiable atmospheric conditions on geodetic measurements and the effects of low reliability of the Instrumentation used still remain the main problems of current monitoring systems. Based on the conclusions of this research, these effects were treated during the monitoring of the UHE Mauá dam.

Chen et al. (2013) carried out a study on the application of GeoMos in the automatic monitoring of a metro protected area where the results showed that the GeoMos working together with the Total Station TM30 meets the requirements for accuracy in monitoring deformation of the metro protected area and provides technical references for deformation monitoring of similar designs.

Also in China, Wenchun and Zhengyuan (2018) researched the application of the GeoMos automatic monitoring software in the monitoring of settlements in the Shenyang subway tunnel, evaluating the accuracy of the collected data and performing feasibility analyzes of this system in the settlement monitoring project . This research established the theoretical importance and practical value of GeoMos for urban rail transit engineering monitoring projects.

In Brazil, researchers from the Geodesy Applied to Engineering group of the UFPR's PPGCG, linked to the CNPq, has been developing research activities in dams since the late 70s, with an emphasis on geodesic auscultation to verify the movement of the earth's crust. Since 2003, researches were also developed for the monitoring of dams.

Da Cruz (2015) integrated the observations derived from the monitoring of dams in the case study of the Mauá HPP, carrying out the analysis and representation of displacements, using error vectors and ellipses, from a computational system specially developed for this purpose.

Jerke (2019) carried out the monitoring of HPP Mauá, integrating GNSS spatial techniques and ground surveys to determine coordinates and analyzed the result of the monitoring carried out with equipment, with precision of 1" and 5", and with different processing software, one commercial for real-time monitoring and another developed by Da Cruz (2015), concluding that both the processing done with the commercial software and the processing performed with the software developed by Da Cruz showed significantly equal results in both analyzed equipment.

In this context, this research aims to analyze the influence of the open spillway, in the result of geodetic monitoring, for the downstream points and the influence of the upstream station position, for the points located on the crest of the UHE Mauá dam. It should be noted that to guarantee the stability of the points of the geodetic reference network, its vertices were tracked during three continuous 8-hour sections using GNSS. This geodetic positioning served to ensure the stability of the network that will be used as a reference for monitoring the irradiated points on the dam body using a robotic total station.

The results found show significant differences in the coordinates both downstream and upstream of the dam.

2. Methodology

For the development of this research, the geodetic monitoring of the Mauá HPP dam was carried out as a case study, and during the work it was verified that some factors can influence the monitoring result.

The Mauá HPP is located in the central-west region of Paraná, positioned at coordinates 24°02'24” of south latitude and 50°41'33” of west longitude, as shown in Figure 1. It is built in the region of Salto Mauá do Tibagi River, on the border between the municipalities of Telêmaco Borba and Ortigueira (LACTEC, 2018).

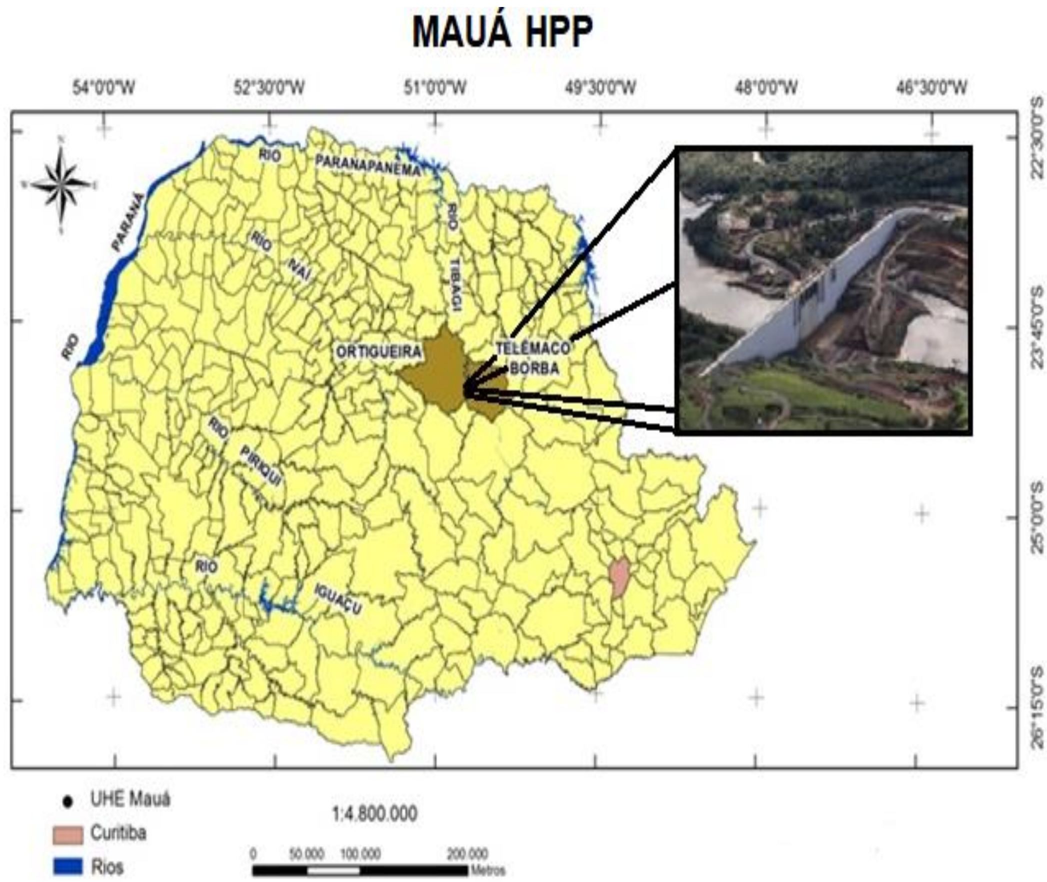

Figure 1 – Location of the Mauá HPP in the state of Paraná.
Source: Siguel (2013).

The reference geodetic network of Mauá HPP is composed of two upstream Geodetic Pillars PG01 and PG02 and a downstream pillar PG03. These have their positions materialized through forced centering systems. In addition, two forced centering devices are installed on the crest of the dam CG01 and CG02 allowing a connection between the upstream and downstream points as shown in Figure 2

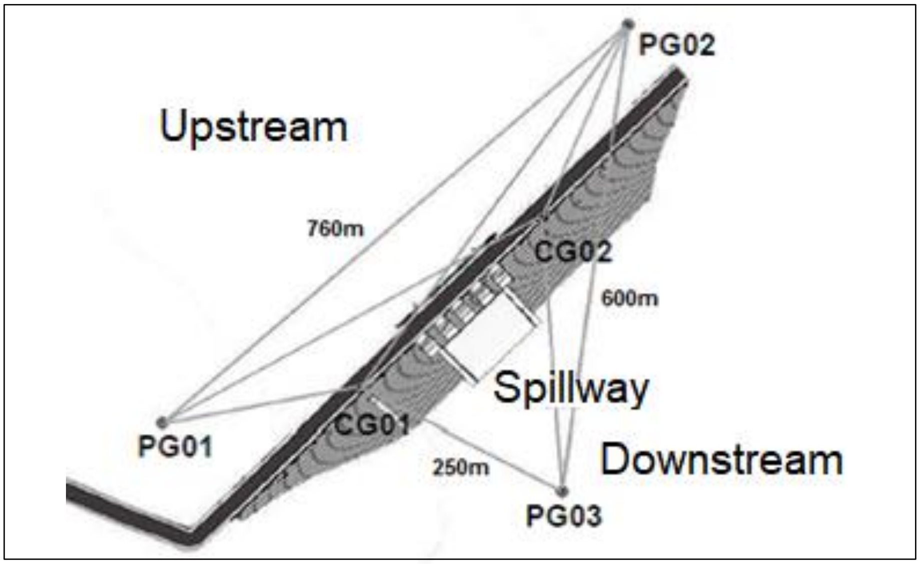

Figure 2 – Arrangement of the Geodetic Reference Network.
Source: Siguel (2013).

The five geodetic landmarks of the network are simultaneously occupied by GNSS receivers with a minimum tracking time of 6 hours. The receivers are identified in relation to the geodetic landmarks in order to use the same landmark-receptor set in all campaigns in order to obtain the coordinates of the pillars with the same equipment.

Two screening sessions were performed at a rate of 5 seconds on 04/24/2018 and 08/09/2018. In processing the GNSS data, a 10º elevation mask and precise ephemeris were used, provided by the IGS – International GNSS Service (IGS, 2018). Calibrated parameters were also used for the receiver antennas, provided by the NGS - National Geodetic Survey (NGS, 2018).

In the adjustment, all possible combinations between the available baselines within a radius of 300 km were analyzed and the best solution found was an arrangement of PG03 with the four closest bases of the Brazilian Network for Continuous Monitoring (RBMC), as shown in Figure 3.

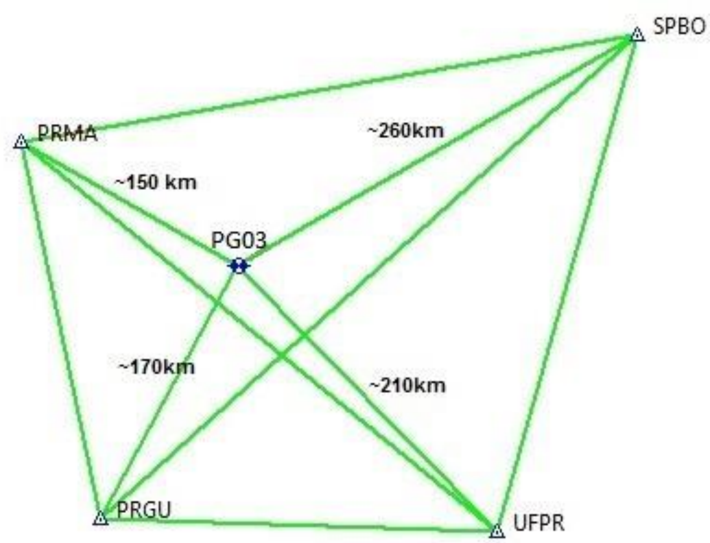

Figure 3 – PG03 GNSS processing geometry.
Source: The authors (2021).

To perform the processing of the other landmarks, the PG03 was used as a reference and by the static relative method, the geodetic coordinates (φ, λ and h) of the other geodetic landmarks were determined as shown in Figure 4.

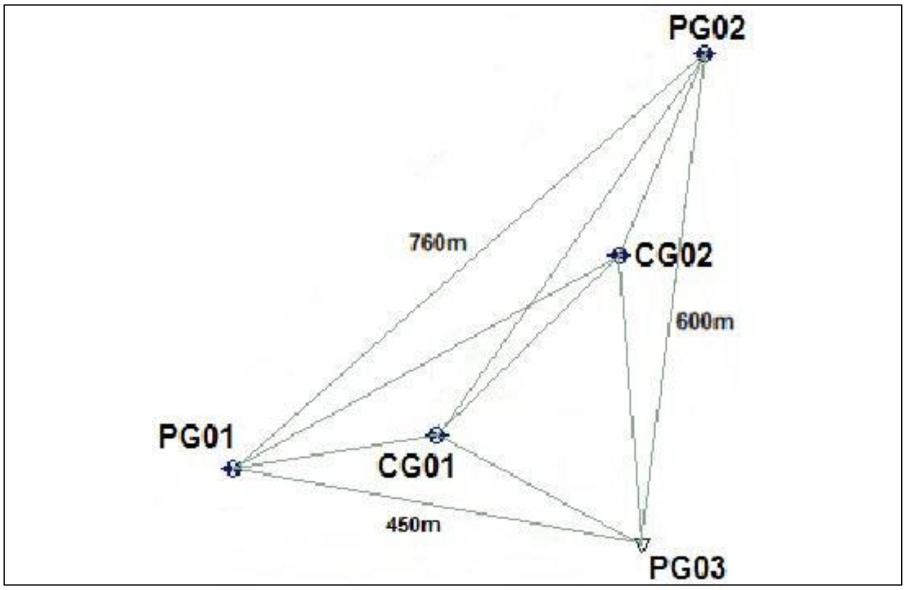

Figure 4 – Processing geometry of the other landmarks.
Source: The authors (2021).

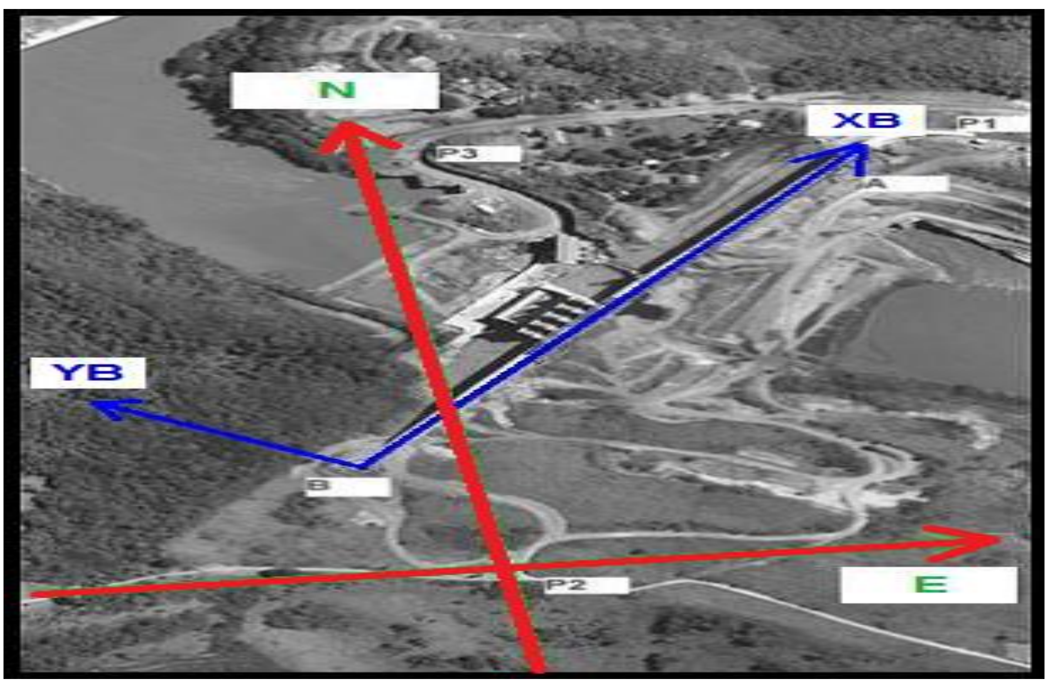

Figure 5 – Transformation for the SB.
Source: Da Cruz (2015).

It was necessary to carry out four monitoring campaigns at the Mauá Hydroelectric Power Plant dam, in order to verify possible movement of monitoring points during the observation period with the spillway open and with the spillway closed.

In the first campaign, with the spillway closed, the GNSS survey of the Geodesic network was carried out and the monitoring points were surveyed using the irradiation technique in order to obtain the reference coordinates. In the second campaign, the GNSS survey of the Geodesic network was carried out again, in order to verify whether or not the pillars used as reference had been moved, as well as the survey of monitoring points to verify the displacement/stability of the monitoring points. As in this campaign the spillway gates were open due to maintenance on the turbines of the SHP (Small Hydroelectric Power Plant), used to maintain the sanitary flow of the Tibagi River, it was suspected that this could influence the coordinates obtained, given that these presented values unexpected. Soon, after finishing the maintenance of the turbines, in order to take advantage of the fact that the water level in the reservoir was practically the same as the previous campaign, a third survey campaign was carried out with the gates closed to assess the influence or not of this phenomenon. Table 1 presents the characteristics of each monitoring campaign.

Table 1 – Campaign characteristics.

Campaign	**Spillway**	**Survey**	**Water level**
First	Closed	GNSS and irradiation	633,43m
Second	Open	GNSS and irradiation	628,87m
Third	Closed	Irradiation	628,52m
Upstream	Closed	Irradiation	Not observed

Source: The authors (2021).

Regarding the upstream monitoring campaign, only one campaign was subsequently carried out since the objective was to compare the coordinates obtained using different points of the geodetic reference network, located on the right, left, upstream and above the dam.

For the survey of the monitoring points downstream in the dam body, the robotic total station was installed and leveled on the PG03 pillar and with a reflector installed in the forced centering device CG01, the orientation of the total station was carried out. For this purpose, the coordinates obtained through the GNSS were used, transformed to the dam system (SB). With the orientation completed, eight measurement series of all prisms located downstream in the dam body were carried out as shown in Figure 6.

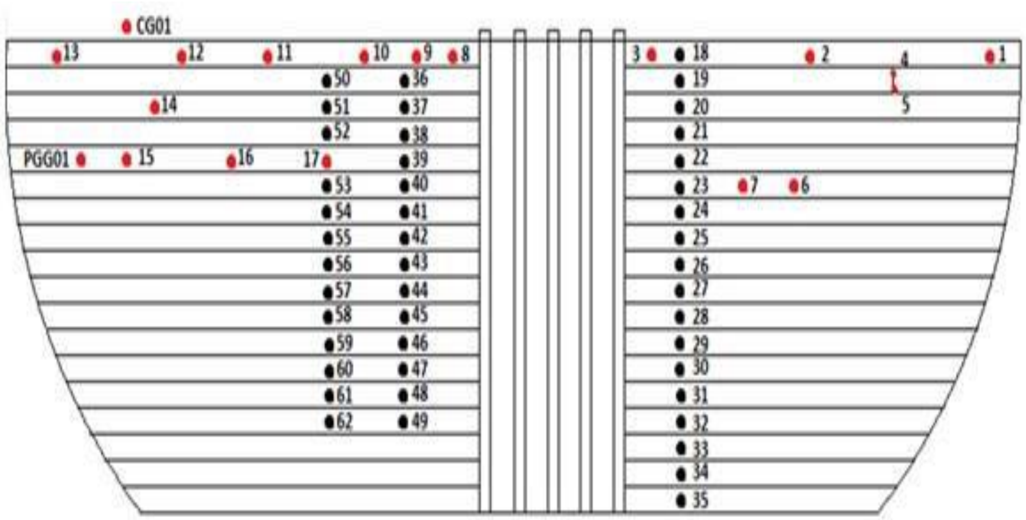

Figure 6 – Location of prisms in the dam body. Source: The authors (2021).

Similarly, the coordinates of monitoring points materialized upstream in the dam were determined. Figure 7 shows the sketches of the views from points PG01, PG02, CG01 and CG02.

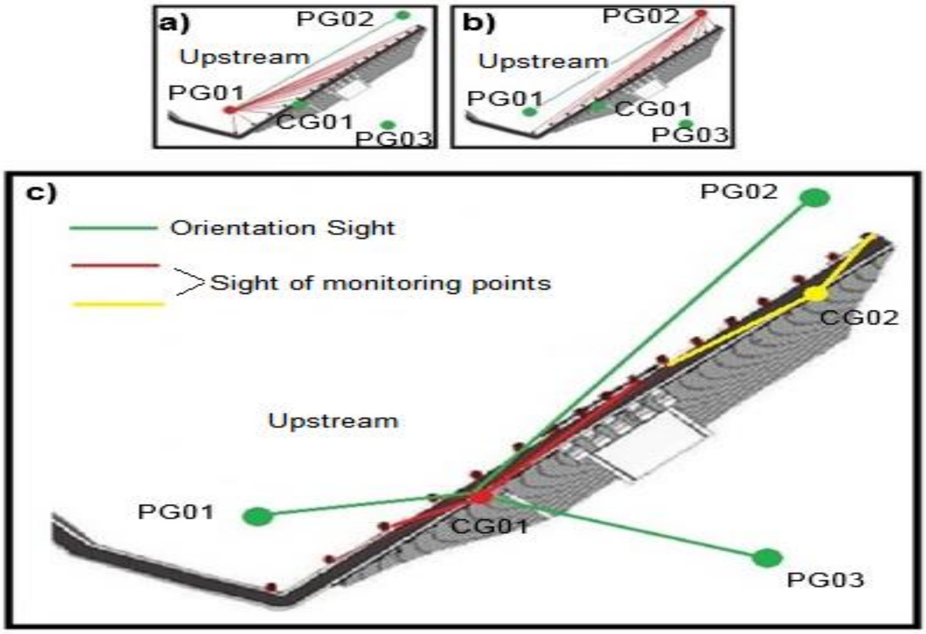

Figure 7 – Indication of the lines of sight.
Source: The authors (2021).

As the sights carried out over the lake are influenced by changes in environmental parameters (temperature and atmospheric pressure) between water and air, which influence the measurement of distance and the calculation of coordinates from the points under influence, PG01 (Figure 7- a) and PG02 (Figure 7-b). To reduce this influence, the same coordinates were determined from two points outside the influence of water refraction, points CG01 and CG02 (Figure 7-c), which are located on the crest of the dam and the sights from them are performed on the bearing race.

After orienting the total station according to each occupied landmark, the monitoring points were targeted. Figure 8 shows the prism in MSU02 and the total station in geodetic frame PG01.

Figure 8 – Upstream monitoring point. Source: The authors (2021).

The correction of each distance measurement was performed using environmental parameters (atmospheric pressure, temperature and relative humidity).

3. Results and discussion

The value of the coordinates of the pillars of the geodetic reference network in the dam system obtained in the first and second monitoring campaign, together with the respective standard deviation, are shown in Tables 2 and 3.

Table 2 – Value of coordinates obtained from the Geodetic Reference Network in the first campaign.

Pillar	**XB (m)**	**σXB (mm)**	**YB (m)**	**σYB (mm)**	**ZB (m)**	**σZB (mm)**
CG01	668,645	0	207,438	0	0,327	1
CG02	352,486	0	207,069	0	0,244	1
PG01	903,835	0	73,731	0	4,644	1
PG02	149,125	0	142,373	0	15,998	1
PG03	653,587	0	453,845	0	-50,052	1

Source: The authors (2021).

Table 3 – Value of coordinates obtained from the Geodetic Reference Network in the second campaign.

Pillar	**XB (m)**	**σXB (mm)**	**YB (m)**	**σYB (mm)**	**ZB (m)**	**σZB (mm)**
CG01	668,645	0	207,437	0	0,328	1
CG02	352,485	0	207,068	0	0,242	1
PG01	903,836	0	73,731	0	4,642	1
PG02	149,123	0	142,373	0	15,998	1
PG03	653,587	0	453,845	0	-50,052	1

Source: The authors (2021).

The difference in the values of the coordinates obtained in the first and second monitoring campaign of the Geodetic Reference Network are shown in Table 4.

Table 4 – Difference in Geodetic Reference Network coordinates between campaigns.

Pillar	**ΔXB (mm)**	**σXB (mm)**	**ΔYB (mm)**	**σYB (mm)**	**ΔZB (mm)**	**σZB (mm)**
CG01	0	0	1	0	-1	1
CG02	1	0	1	0	2	1
PG01	-1	0	0	0	2	1
PG02	2	0	0	0	0	1
PG03	0	0	0	0	0	1

Source: The authors (2021).

Considering that there were no significant variations, within a 95% significance level, of the coordinates obtained at different times, the coordinates of the Geodetic Reference Network were used to guide the survey on the dam body. In the third campaign and in the upstream campaign, the coordinates of the geodetic network of the second campaign were considered, given that both were carried out only 18 days after the second campaign.

Table 5 shows the average of the difference in coordinates between the first and second monitoring campaign of the downstream points.

Table 5 – Difference in coordinates between the first and second campaigns.

Difference between first - second campaign					
ΔXB (mm)	**σXB (mm)**	**ΔYB (mm)**	**σYB (mm)**	**ΔZB (mm)**	**σZB (mm)**
-4	1	**-5**	2	**5**	1

Source: The authors (2021).

Comparing the first campaign with the second, unexpected variations in the XB axis can be seen, where the difference in coordinates in XB resulted in an average value of -0.004 ± 0.001m, indicating possible lateral displacements in all monitoring points. As in dams there are almost no lateral forces acting on the structure, to analyze whether there was a possible lateral displacement, another survey campaign was carried out to prove this hypothesis. It is also worth remembering that in the first campaign the spillway gates were closed and in the second campaign the spillway gates were open, with this it was suspected that the spilled water could influence the results of the geodetic monitoring of the dam. One more monitoring campaign was then carried out with the gates closed, soon after the gates were closed due to maintenance on the turbines, in order to use the same level of water as in the previous campaign.

Table 6 shows the difference in the mean of the coordinates found between the second and third monitoring campaign, with the third campaign being carried out 18 days after the second campaign and in the two campaigns there was no significant difference in the water level in the reservoir.

Table 6 – Difference in coordinates between the second and third campaigns.

Difference between second - third campaign					
ΔXB (mm)	**σXB (mm)**	**ΔYB (mm)**	**σYB (mm)**	**ΔZB (mm)**	**σZB (mm)**
3	1	**2**	2	**-5**	1

Source: The authors (2021).

As displacements in XB continued to present unexpected values in the second – third campaign with an average value of 0.003 ± 0.001m, even with a minimum time interval of 18 days and with an insignificant difference in the reservoir water level of 0.35m, the behavior of coordinates between campaigns with the same conditions was analyzed, that is, campaigns with closed floodgates (first – third).

Table 7 shows the difference in the average of the coordinates found between the first and third monitoring campaign, analyzing the campaigns that had the floodgates closed

Table 7 – Difference in coordinates between the first and third campaign.

Difference between first - third campaign					
ΔXB (mm)	**σXB (mm)**	**ΔYB (mm)**	**σYB (mm)**	**ΔZB (mm)**	**σZB (mm)**
-1	1	**-3**	2	**0**	1

Source: The authors (2021).

Analyzing the results of the campaigns with the closed floodgates, the coordinate differences in XB presented a mean value of -0.001 ± 0.001m, it appears, therefore, that there is no indication of lateral movement, within a significance level of 95% and considering the accuracy of the equipment used.

In YB, the difference in the coordinates found between the campaigns varied significantly, with the difference found in the first - second campaign (open floodgates) the value found was -0.005 ± 0.002m, in the second - third campaign the value was + 0.002 + 0.002m (open gates) and in the first – third (closed gates) the value was -0.003 ± 0.002m. As shown in the text, the YB axis is in the direction of the river's flow, therefore, as in the second and third campaign the reservoir level decreased by approximately 5m compared to the first campaign, the forces and pressure against the dam decreased, which could be a possible cause of the negative variation found in the value of the coordinate differences. When analyzing the campaigns that did not have a significant difference in the water level of the reservoir (second – third campaign), the result found for the difference in coordinates was 0.002 + 0.002, and it cannot be said that there was movement of the points considering the accuracy of the equipment.

In ZB, the behavior was practically the same as in XB, because in the campaign with open floodgates the average value was 0.005 ± 0.001m and in the campaign with closed floodgates the average value was 0.000 ± 0.001m.

From these results, it can be seen that the fact that the floodgates are open, the spilled water can influence the obtainment of the coordinates of the points downstream and, consequently, the result of the geodetic monitoring of the dam.

For the study of the coordinates of the upstream points, it was decided to use only one monitoring campaign and to analyze the differences between the coordinates of the monitoring points, obtained through different pillars of the geodetic network (PG01, PG02, CG01 and CG02) seeking verify the existence of the influence of the refraction caused by the reservoir. Table 8 contains the differences between the coordinates obtained from PG01 and PG02, where measurements were under the influence of the reservoir.

Table 8 – Difference of coordinates of upstream columns PG01 and PG02.

Points	**XB (mm)**	**σXB (mm)**	**YB (mm)**	**σYB (mm)**	**ZB (mm)**	**σZB (mm)**
MSU01	**-1**	0	**7**	2	**0**	1
MSU02	**0**	1	**8**	2	**6**	1
MSU03	**1**	1	**7**	1	**8**	2
MSU04	**2**	0	**7**	1	**12**	2
MSU05	**0**	0	**7**	1	**16**	1
MSU06	**2**	1	**9**	1	**22**	1
MSU07	**0**	0	**8**	1	**28**	1
MSU08	**0**	1	**10**	2	**30**	3
MSU09	**0**	1	**9**	2	**35**	1
MSU10	**0**	0	**8**	1	**37**	1

Source: The authors (2021).

In Tables 9 and 10, it is possible to observe the differences between the coordinates obtained from the columns PG01 and PG02, respectively, and the forced centering devices CG01 and CG02, which are not under the influence of the reservoir. It should be noted that from landmark CG01 it is possible to observe only the points from MSU01 to MSU 07 and from landmark CG02 it is possible to observe the other monitoring points upstream. As it is not possible to observe all monitoring points from CG01 and CG02, the results of the differences found in tables 9 and 10 were unified.

Table 9 – Difference of coordinates of upstream column PG01 in relation to CG01 and CG02.

Points	XB (mm)	σ XB (mm)	YB (mm)	σ YB (mm)	ZB (mm)	σZB (mm)
MSU01	**-2**	0	**16**	1	**110**	1
MSU02	**-3**	0	**19**	1	**108**	2
MSU03	**-1**	0	**15**	1	**114**	1
MSU04	**-1**	0	**13**	1	**115**	1
MSU05	**-2**	0	**12**	0	**118**	1
MSU06	**-1**	0	**10**	0	**120**	0
MSU07	**-3**	0	**10**	1	**120**	1
MSU08	**-7**	0	**4**	2	**333**	1
MSU09	**-6**	1	**3**	1	**340**	1
MSU10	**-7**	1	**4**	2	**341**	1

Source: The authors (2021).

Table 10 – Difference of coordinates of upstream column PG02 in relation to CG01 and CG02.

Points	XB (mm)	σ XB (mm)	YB (mm)	σ YB (mm)	ZB (mm)	σZB (mm)
MSU01	**-1**	0	**9**	2	**110**	2
MSU02	**-3**	0	**10**	2	**102**	3
MSU03	**-2**	0	**7**	1	**105**	2
MSU04	**-2**	0	**6**	1	**104**	2
MSU05	**-2**	0	**5**	1	**102**	1
MSU06	**-3**	0	**1**	1	**98**	1
MSU07	**-7**	0	**-4**	2	**305**	1
MSU08	**-6**	0	**-7**	2	**310**	2
MSU09	**-7**	0	**-5**	1	**306**	1
MSU10	**-7**	0	**-5**	1	**305**	1

Source: The authors (2021).

Considering the results of tables 8, 9 and 10, together with the propagation of covariance to obtain the coordinates of the upstream monitoring points, it is clear that at each landmark used to perform the measurement, there is a significant difference in the value of the coordinates obtained at the upstream monitoring points, and the values of these coordinate differences are greater than the influence of the precision of the instrument used.

This analysis discards the possibility that these values indicate the movement/displacement of these points since the measurements of all points through all landmarks were carried out in the same campaign, that is, they were carried out on the same day.

Thus, it was found that depending on the landmark used to obtain the upstream coordinates, there is the possibility that the atmospheric refraction caused by the water reservoir influences the value of the coordinates of the upstream monitoring points.

4. Final considerations

Regarding the stability of the geodetic reference network, we can state that the differences between the coordinates obtained at different times, within a 95% significance level, are insignificant. As a result, the coordinates obtained in the first campaign were used as a reference for surveying the body of the dam for all campaigns.

For the monitoring of the downstream points, it was found that the results between campaigns with the spillway under different conditions (a campaign with open gates and another campaign with closed gates) show different values, indicating lateral movement in the dam. When analyzing the campaigns with the spillway under the same conditions (both campaigns with the gates closed), the results show values compatible with the forces exerted on the dam, as the difference in the coordinates in YB indicates that there is a variation in the same direction of flow from the river, where there is a greater influence of force and pressure applied to the dam, within acceptable limits, due to the drop of approximately 5 meters in the reservoir water level between the analyzed campaigns.

Thus, it is concluded that during the geodetic monitoring of a downstream dam, the fact that the dam is leaking can interfere with the value of the obtained coordinates and, consequently, with the result of the monitoring.

Regarding upstream monitoring, it was found that when obtaining the coordinates from the left bank (PG02), right bank (PG01) or over the dam crest (CG01 and CG02), the results are different depending on the landmark used to perform the measurement. Through this finding, a research was started, being conducted in a doctoral thesis at the Federal University of Paraná to evaluate the influence of the refraction coefficient as a function of the characteristics and size of the surface area of water in the reservoir, in the geodetic monitoring of dams.

Analyzing the results obtained, it is recommended that the monitoring result be carried out through the embedded points in the facing of the dam downstream to avoid the influence of refraction of the reservoir water and that the monitoring campaigns be carried out with the spillway closed. Regarding upstream monitoring, great care is recommended with the lateral refraction modeling to minimize the distortion of the horizontal coordinates (XB and YB). For the determination of the vertical coordinate (ZB), also called settlement, it is recommended to use the first order geometric leveling technique, a method of equal sights which, when used correctly, minimizes the effects of refraction, of the curvature of the earth and the vertical collimation of the instrument.

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