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HOW EFFECTIVE IS MONITORING CONCRETE DAMS WITH GNSS IN 3D MODE?

José Nuno Lima[1]
LNEC

ABSTRACT

Since GNSS is a three-dimensional satellite positioning and navigation system, however, it is unusual to monitor dams in the altimetric component with this system, but only in the two horizontal components. Thus, the third component of three-dimensional positioning guaranteed by GNSS is wasted. There are two main reasons to justify this practice: firstly, because vertical positioning with GNSS is around two to three times less precise than horizontal positioning; and secondly, because spirit levelling allows for very precise and still very expedient vertical positioning, although it is very difficult to implement automatically.

The aim of this work is to quantify the effectiveness of GNSS in 3D monitoring of concrete dams, based on Portuguese experience of monitoring these structures with such a system.

Keywords: 3D Monitoring, Vertical uncertain, GNSS, Concrete Dams, Time Series.

[1]jnplima@lnec.pt, Portugal

1. INTRODUCTION

In so-called classical geodesy, planimetry has always been treated separately from altimetry. The reason for this separation, according to the specific literature of this science at the time (e.g., [1]), was the difficulty of correcting for the effects of atmospheric refraction, which tended to affect altimetry more than planimetry. In fact, the computations on either the ellipsoidal surface or the conformal map are inherently two-dimensional. The points are parameterised in terms of geodetic latitude and longitude or conformal mapping coordinates. Networks on the ellipsoidal surface or the conformal map have historically been labelled “horizontal networks” and treated separately from a one-dimensional “vertical network”. Such a separation was justified at a time, in addition to the justification already given, when the measurement tools could be readily separated into those that measured primarily “horizontal information” and those that yielded primarily “vertical information”. GNSS breaks this separation because it provides accurate three-dimensional positions [2]. However, the question arises: is the altimetry measured by GNSS accurate enough for monitoring the displacement of concrete dams, where the uncertainty should be of the order of one millimetre? On the other hand, spirit levelling (also known as geometric levelling or direct levelling) is very precise and still expedient, and is always a direct competitor to the altimetric monitoring obtained with GNSS.

Since 2016, some concrete dams in Portugal have been monitored with great success using continuous GNSS, but only in the horizontal component. Although GNSS provides observations in 3D mode, the altimetric component has not yet been used in this monitoring.

It is well known that the accuracy obtained with GNSS in the altimetric component is around 3 times less precise than that obtained with GNSS in the horizontal component (tests carried out on the LNEC campus also confirm this result). It is also important to note that at the scale of a civil engineering structure, i.e. locally, monitoring the altimetric component is practically equivalent to monitoring the vertical component. The altimetric component observed by GNSS is measured along to the normal to the ellipsoid, and the orthometric height is measured along to the vertical direction. However, locally the variations of these two quantities are equivalent. In the literature, orthometric height is often informally referred to as elevation.

The aim of this article is to assess the accuracy of altimetric monitoring of concrete dams as a function of the distance between the reference station and the object points and the height differences between them. Finally, it concludes on the effectiveness of GNSS in the altimetric monitoring of concrete dams.

2. GNSS DAM MONITORING SYSTEMS

This section provides a summary of the GNSS dam monitoring systems installed in four large dams in Portugal.

2.1. Baixo Sabor dam

The Baixo Sabor dam is located in north-eastern Portugal on the lower reaches of the Sabor River, a tributary of the right bank of the Douro River. The Baixo Sabor dam is a double arch dam with a height of 123 m and a total crest length of 505 m.

Four permanent GNSS stations were installed: three located on the crest of the dam, in blocks 10-11, 16-17 and 23-24 (Figure 1), and one located on the right bank, to work as a reference station.

The GNSS reference station (REFM) of the dam was installed on the right bank, on the top of a 4 m high reinforced concrete pillar. The GNSS receiver of this station was installed in a technical cabinet at the base of the pillar. The average distance between the station on the crest and the reference station is 645 m, with an average height difference of about 267 m.

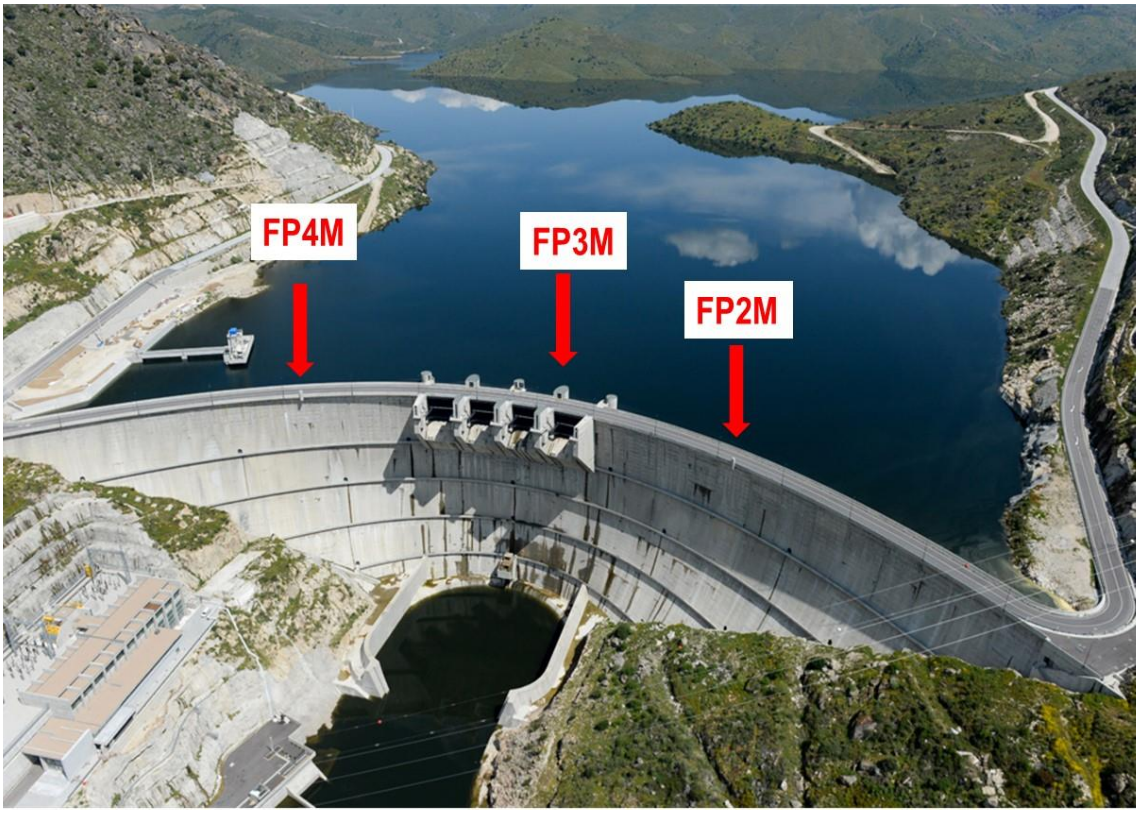

Fig. 1 – Location of GNSS stations at the Baixo Sabor dam: FP2M, FP3M, FP4M, on the dam crest

2.2. Cabril dam

The Cabril dam is located in the centre of Portugal, on the Zêzere river, which is part of the Tagus River basin. The Cabril dam is a double curvature arch dam with a maximum height above the foundation of 132 m and a total crest length of 290 m.

For the GNSS dam monitoring system two permanent GNSS stations were installed: one located on the crest of the dam, in the K-L block, and the other located on the left bank, to work as a reference station (Figure 2).

The reference GNSS station was installed on the left bank, on the top of a medium voltage pole of a deactivated power line, which was cut to a height of about 6 m. The GNSS receiver of this station is installed in a technical cabinet inside of geodetic pillar shelter, close to the former medium voltage pole. The distance between the station on the crest and the reference station is 240 m, with a height difference of 0.5 m.

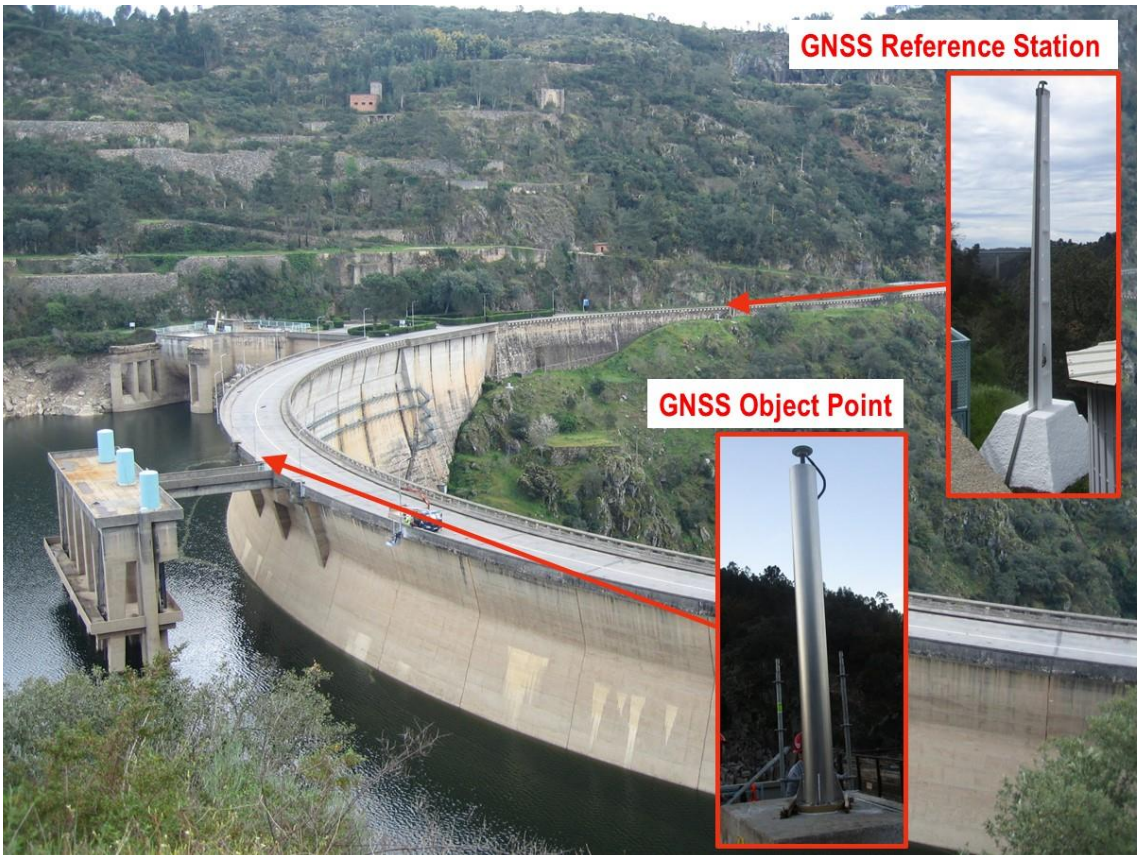

Fig. 2 – Location of GNSS stations at Cabril Dam: Reference station, left bank, and object point, crest of the dam

2.3. Feiticeiro dam

The Feiticeiro dam is located in the north-east of Portugal, on the lower reaches of the Sabor River, a tributary of the right bank of the Douro River. The Feiticeiro dam is a straight-axis concrete dam with a height of 45 m and a total crest length of 315 m.

For the GNSS dam monitoring system four permanent GNSS stations were installed: three located on the crest of the dam, in blocks 06-07, 11-12 and 16-17, and one located on the right bank, to work as a reference station (Figure 3).

The GNSS reference station (REFJ) of the dam was installed on the right bank, on top of a 3 m high reinforced concrete pillar. The GNSS receiver of this station is in a technical cabinet at the base of the pillar. The average distance between the station on the crest and the reference station is about 360 m, with an average height difference of around 60 m.

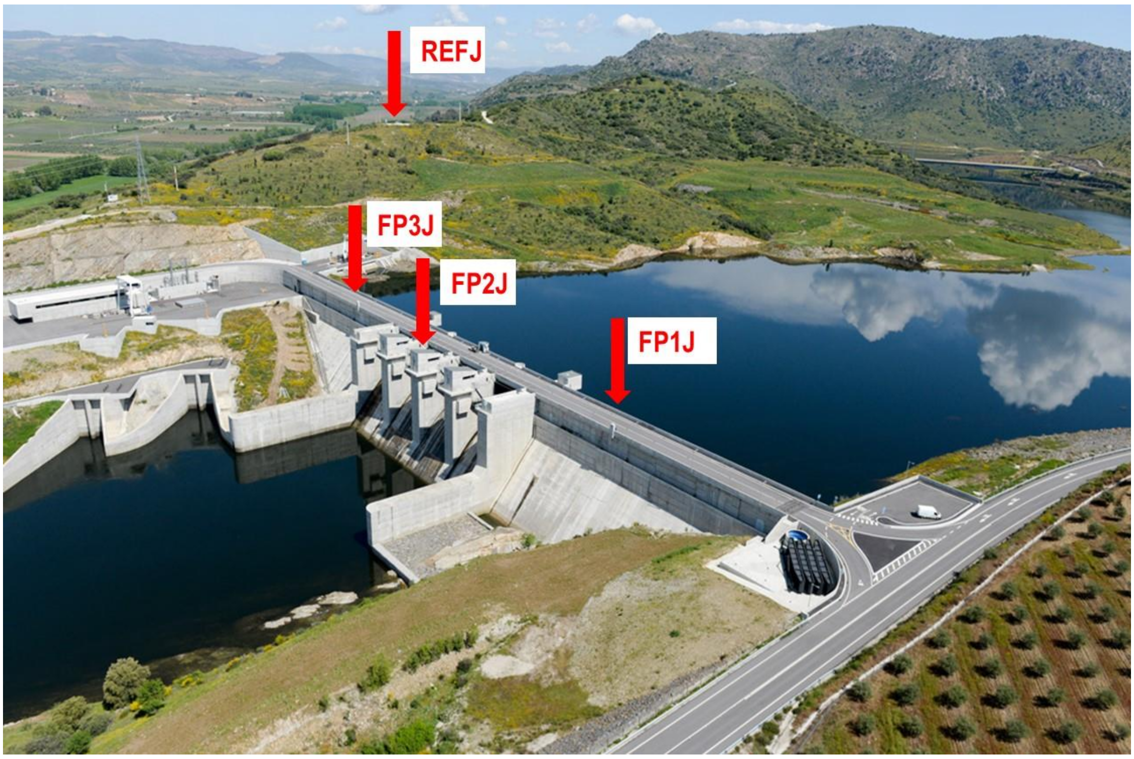

Fig. 3 – Location of the GNSS stations at the Feiticeiro dam: FP1J, FP2J, FP3J, on the dam crest, and REFJ, as a reference station, on the right bank

2.4. Foz Tua dam

The Foz Tua dam is located in the northern region of Portugal, on the Tua River, an important tributary of the Douro River, near its confluence with the Douro River. Foz Tua is a double arch dam with a height of 108 m and a total crest length of 275 m.

The GNSS dam monitoring system consists of two permanent GNSS stations: one located on the crest of the dam, in E2E1 block, and the second located on the right bank, to work as a reference station (Figure 4).

The reference GNSS station was installed on the right bank, on the top of a 2 m high reinforced concrete pillar. The GNSS receiver of this station is in a technical cabinet near by the pillar.

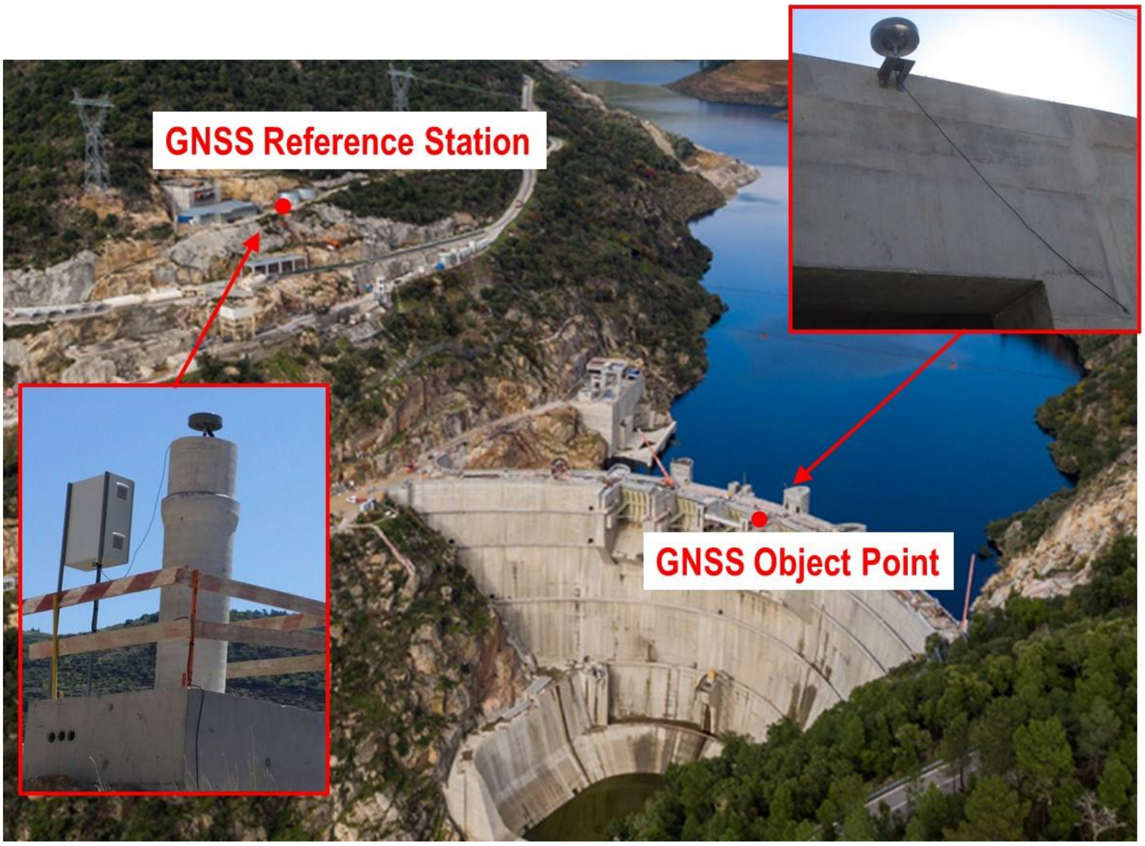

Fig. 4 – Location of GNSS stations at Foz Tua Dam: Reference station, left bank, and object point, crest of the dam

The distance between the station on the crest and the reference station is 242 m, with a height difference of 80 m.

3. LINEAR FILTER, GAIN, PHASE SHIFT AND MOVING AVERAGE

A linear combination of the terms of a time series ($x_0,x_1,...,x_n$):

$$y_k = \sum_{j=-q}^{r} w_j x_{k+j} \quad (k = q+1, \ldots, n-r) \tag{1}$$

where the m (= q + r + 1) coefficients w_j are weights, is called linear filter of order m. If q = r and $w_j = w_{-j}$, the filter is said to be symmetric. If the weights sum up to one, the filter is called a weighted moving average. If the weights are equal and sum up to one, the filter is called a simple moving average [4].

The application of a filter to a time series (the input time series ($x_0,x_1,...,x_n$)) produces a new time series (the output time series ($y_0,y_1,...,y_n$)). The spectral characteristics of the output series are related to the spectral characteristics of the input series by means of the transfer function of the filter. The transfer function is a complex function with arguments in the frequency domain. The modulus of the transfer function is called the gain of the filter [5]. The argument of the transfer function is called the phase shift of the filter [5].

If the gain of the filter, for a given angular frequency (ω), is greater than one, the filter amplifies the input series in that frequency. Otherwise, if the gain of the filter, for (ω), is lesser than one, the filter smooths the input series in that frequency.

Besides the change in amplitude the filter may also introduce a phase shift on the output time series depending on the frequency. Though the symmetric filters do not introduce significant phase shifts, the asymmetric ones do.

4. ANALYSIS OF VERTICAL DISPLACEMENTS OBSERVED WITH GNSS

4.1. General considerations

The estimated uncertainty for hourly solutions of the horizontal components is about 5 times greater than the estimated uncertainty for the daily solutions of the horizontal components [3]. However, hourly solutions have a higher temporal resolution than daily solutions. The application of symmetric moving averages to hourly solutions allows a significant reduction in uncertainty without compromising temporal resolution (e.g. the 25th order symmetric moving average reduces de the uncertainty of the time series hourly solutions from 4 mm to 0,8 mm at the Baixo Sabor dam [3], but in horizontal components). Moving averages act as a low pass filter and are very easy to implement in time series. So now it's time to ask the following question: how will the vertical component behave in daily, hourly or even less frequent time series? It’s already known, as mentioned in the 1. Introduction, that the accuracy obtained with GNSS in the altimetric (vertical) component is about 3 times less accurate than the corresponding accuracy in the horizontal component. The explanation is that the modelling errors in the tropospheric delay are strongly correlated with the estimation errors in the (vertical) height component [6]. In addition, the altitude component is also affected by the fact that GNSS satellites are not uniformly distributed across the sky (e.g., GPS satellite orbits are inclined at 55º to the equatorial plane).

4.2. Baixo Sabor dam

The Figure 5 shows the results of the applying a 25th order symmetric moving average to the time series of observed displacements, vertical components, at the FP2M, FP3M and FP4M stations of the Baixo Sabor dam. The orange dots represent the vertical displacements observed by the GNSS at FP2M (hourly solution with the application of the 25th order symmetric moving average to the time series). The grey dots represent the vertical displacements observed by the GNSS at FP3M (idem). The light blue dots represent the vertical displacements observed by the GNSS at FP4M (idem). The yellow dots represent the vertical displacements observed by the spirit levelling at NC1011 (benchmark near FP2M). The black dots represent the vertical displacements observed by the spirit levelling at NC1617 (benchmark near FP3M). The purple dots represent the vertical displacements observed by spirit levelling at NC2324 (benchmark near FP4M). The moving averages of order 25 applied to the time series of vertical displacements observed by GNSS are still too noisy to be analysed graphically, as can be seen in Figure 5. Increasing the order of the moving averages, for example to 168 (corresponding to a weekly average), allows the time series to be smoothed, as can be seen in Figure 6. Maintain the conventions used for the observables in Figure 5.

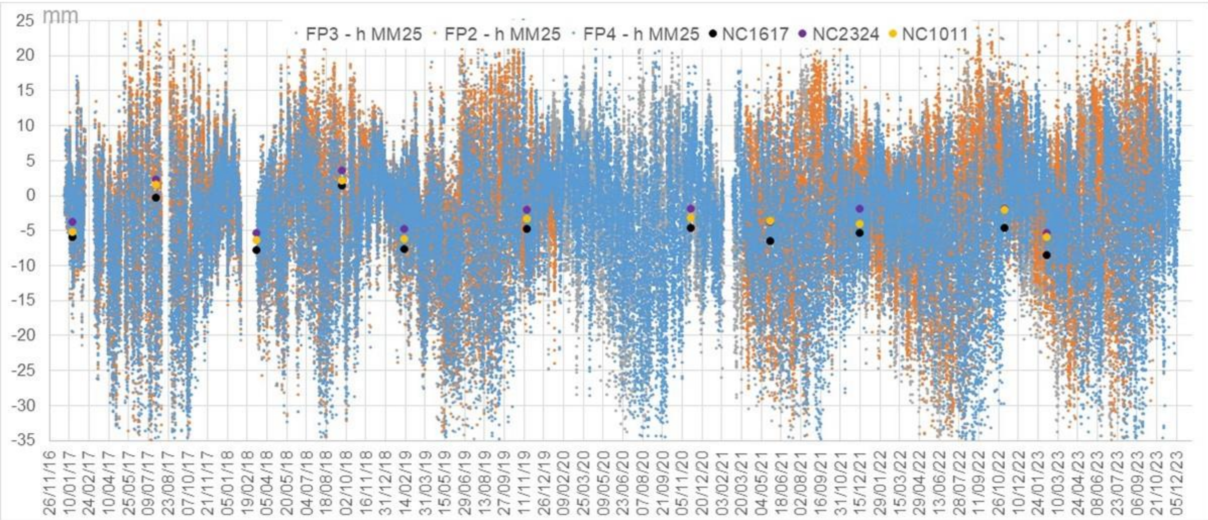

Fig. 5 – The results of the application of 25th order moving average to the time series of GNSS observed displacements, vertical components, in FP2M, FP3M e FP4M station of Baixo Sabor dam

Or by applying moving averages of order 500 (corresponding to an average of 21 days) to the time series of displacements observed by GNSS, as shown in Figure 7 (using the same conventions as in the previous figures).

Finally, by applying moving averages of order 2000 (corresponding to an average of 83 days) to the time series of displacements observed by GNSS, as shown in Figure 8 (using the same conventions as in the previous figures).

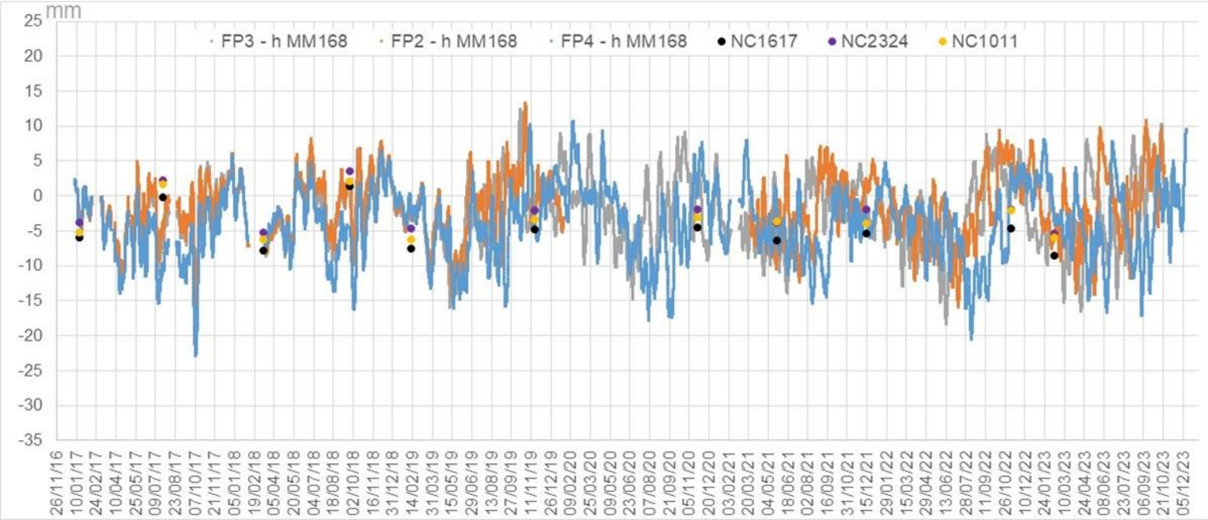

Fig. 6 – The results of the application of 168th order moving average to the time series of GNSS observed displacements, vertical components, in FP2M, FP3M e FP4M station of Baixo Sabor dam

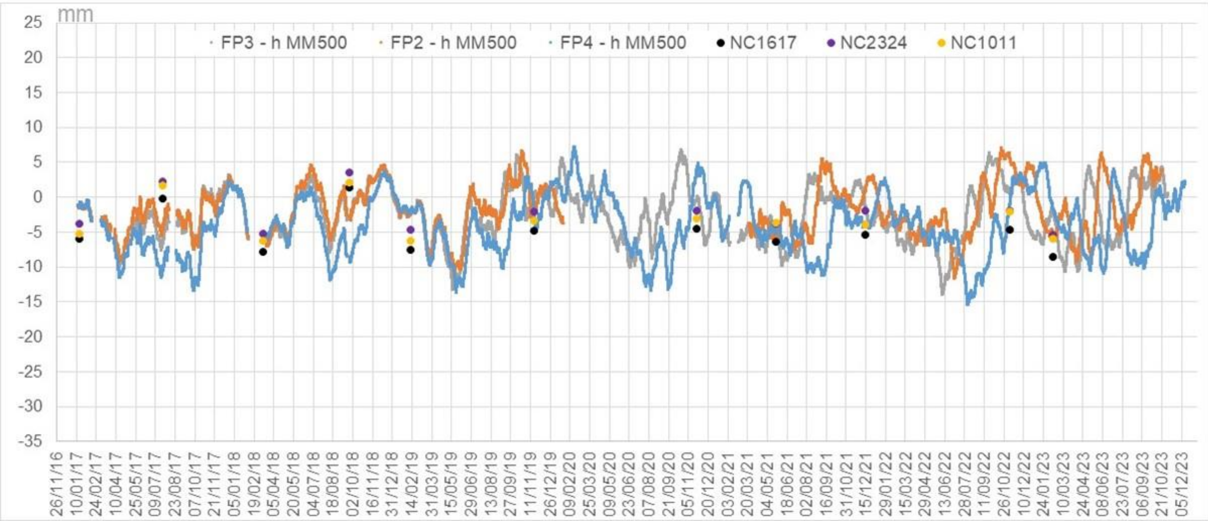

Fig. 7 – The results of the application of 500th order moving average to the time series of GNSS observed displacements, vertical components, in FP2M, FP3M e FP4M station of Baixo Sabor dam

A moving average of such a high order, as in the cases presented above, runs the risk of dissipating any significant effect caused by a large variation in reservoir level or a marked change in average temperature over one or more weeks. However, the uncertainty in the height component (vertical displacements) in this dam is greatly affected by the difference in height between the reference GNSS station and the GNSS stations on the crest, around 267 metres, more than the distance between them (the average is around 645 metres), which is nevertheless not significant in increasing the uncertainty in relative 3D positioning with GNSS.

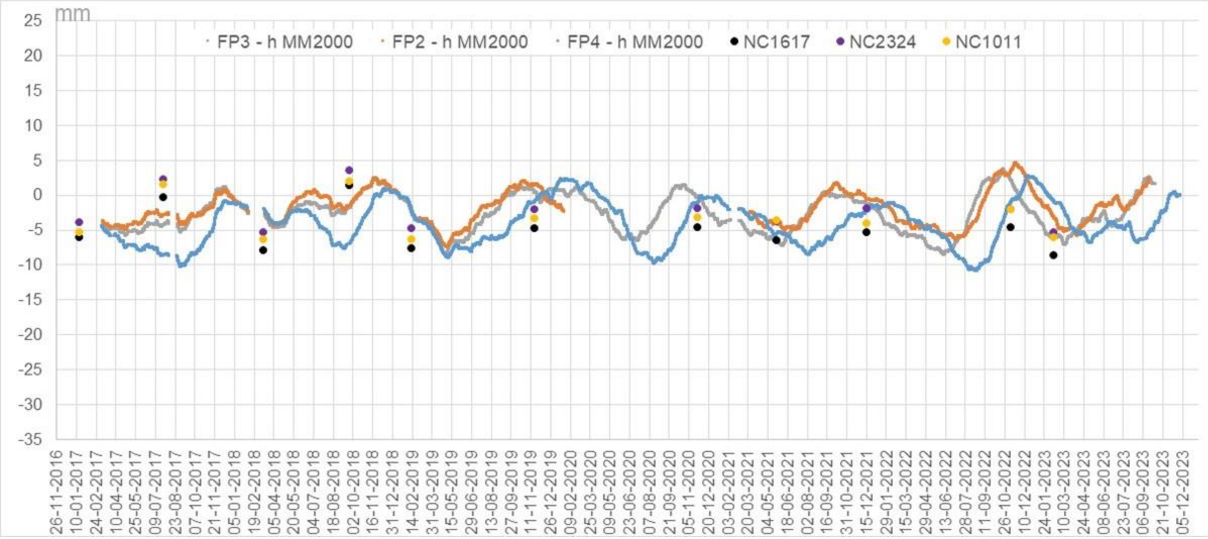

Fig. 8 – The results of the application of 2000th order moving average to the time series of GNSS observed displacements, vertical components, in FP2M, FP3M e FP4M station of Baixo Sabor dam

Figures 5 to 8 give a graphical idea of the differences between the vertical displacements observed by GNSS and those observed by spirit levelling at the benchmarks closest to the GNSS stations, but not the numerical differences, which are given in Table 1 and the values are expressed in mm. This table also shows the respective standard deviations and the average standard deviation. Due to space limitations, not all differences between the moving average of order 2000 and the spirit levelling are shown.

Table 1 – Differences in vertical displacements observed between GNSS and spirit levelling

FP2 mm25 – NC1011	FP3 mm25 – NC1617	FP4 mm25 – NC2324	FP2 mm168 – NC1011	FP3 mm168 – NC1617	FP4 mm168 – NC2324	FP2 mm500 – NC1011	FP3 mm500 – NC1617	FP4 mm500 – NC2324	FP3 mm2000 – NC1617
1.7	1.0	2.1	-3.5	-3.5	-3.4	-1.5	-1.5	-1.4	-
-11.5	-17.9	-14.6	-4.2	-10.3	-6.5	-4.6	-10.8	-6.7	-8.8
-4.8	-3.6	-2.8	-2.1	-2	-2.3	-2.5	-2.3	-2.6	-2.0
0.1	-5	-1.4	-3.3	-1.3	-4	-1	-2.7	-1.6	-0.4
-	2.7	4.6	0.7	0	2.3	-	-6.9	-6.7	-0.6
-9.3	-10.5	-11.5	-9.2	-9.1	-9	-5.4	1.9	3.2	-5.9
3.1	-0.1	2.2	6	3.2	5.1	5.8	2.9	4.9	0.5
-6.1	-5.1	-6.4	-6.3	-6	-6.7	-5.2	-5.1	-5.7	-3.0
StaDesv	StaDesv	StaDesv	StaDesv	StaDesv	StaDesv	StaDesv	StaDesv	StaDesv	StaDesv
6.47	7.72	7.44	3.68	3.79	3.92	1.90	4.69	5.49	4.19
Average StaDesv			Average StaDesv			Average StaDesv			Average StaDesv
7.21			3.80			4.03			2.75

Table 1 shows that the uncertainty in the GNSS observed vertical displacements, which in this particular case is strongly influenced by the height differences between the GNSS stations, is too high to monitor a concrete dam. Even with the application of high order moving averages, and despite the progressive smoothing of the observed time series, the corresponding standard deviations are still very high, this is still far from the 1 mm accuracy required for monitoring concrete dams.

Spirit levelling campaigns are carried out every year. For reasons of timing, these campaigns are not always carried out in the same month.

4.3. Cabril dam

In the case of the Cabril dam, in addition to the distance of only 240 metres between the GNSS reference station and the GNSS crest station, the most significant factor is the difference in height between these two stations, which is only 0.5 metres. Figure 9 shows the height variations of the GNSS station at the crest, using a 25th order moving average, and the corresponding 500th order moving average in blue and brown, respectively. The black dots represent the height variation observed by spirit levelling at the KL block benchmark, all expressed in millimetres. Finally, in red is the 168th order moving average of temperatures (corresponding to one week), expressed in degrees Celsius.

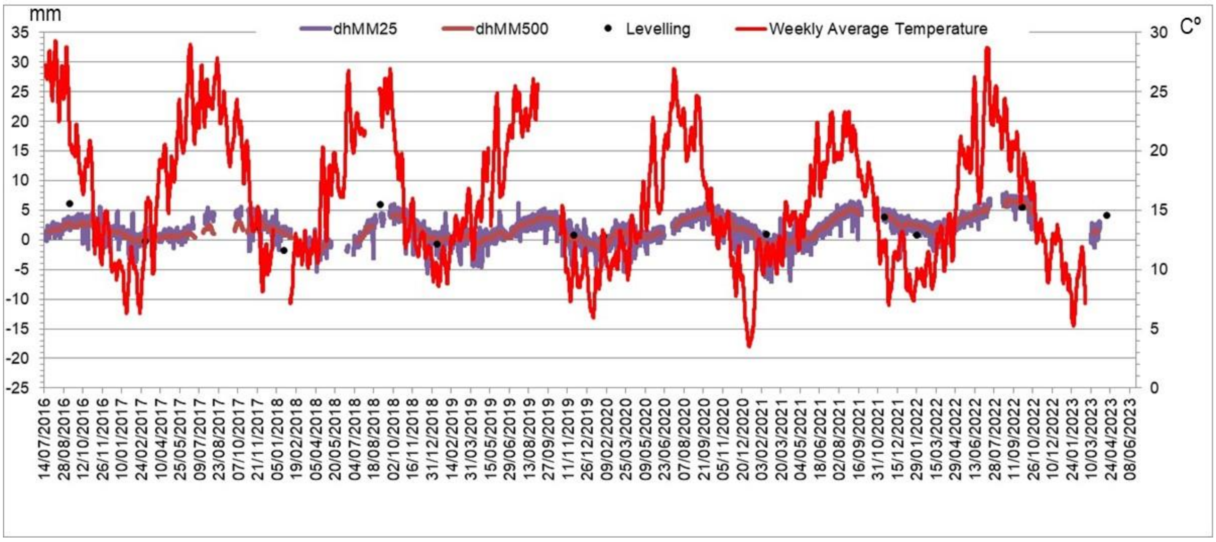

Fig. 9 – The results of the applications of 500th and 25th order moving average to the time series of GNSS observed displacements, vertical components, in block KL station of Cabril dam, plus weekly average temperature and spirit levelling

Unlike the previous case, here the 25th order moving average appears to be accurate enough to be compared with the spirit levelling time series. But let's analyse in more detail these comparisons between the 25th and 168th order moving averages of the hourly time series of dam height variation in the KL block with GNSS and compare them with geometric levelling

(Figure 10). In Figure 11, only the 168th order moving average is replaced by the 500th order moving average (using the same conventions as in the previous figures).

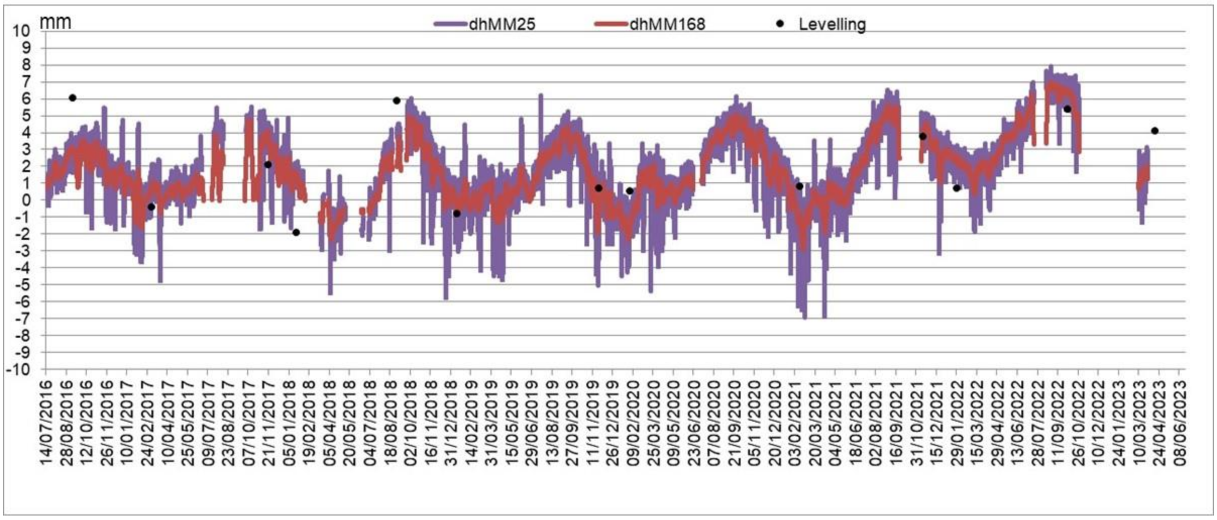

Fig. 10 – The results of the applications of 500th and 25th order moving average to the time series of GNSS observed displacements, vertical components, in block KL station of Cabril dam, plus weekly average temperature and spirit levelling

Figures 10 and 11 show that, in this case, there is no advantage in increasing the order of the moving average to improve the accuracy of the time series of the height variation of the Cabril dam observed by GNSS. Table 2 shows the numerical values observed by the two completely independent techniques, the respective differences, the mean values of the differences and the standard deviations of the differences (expressed in millimetres).

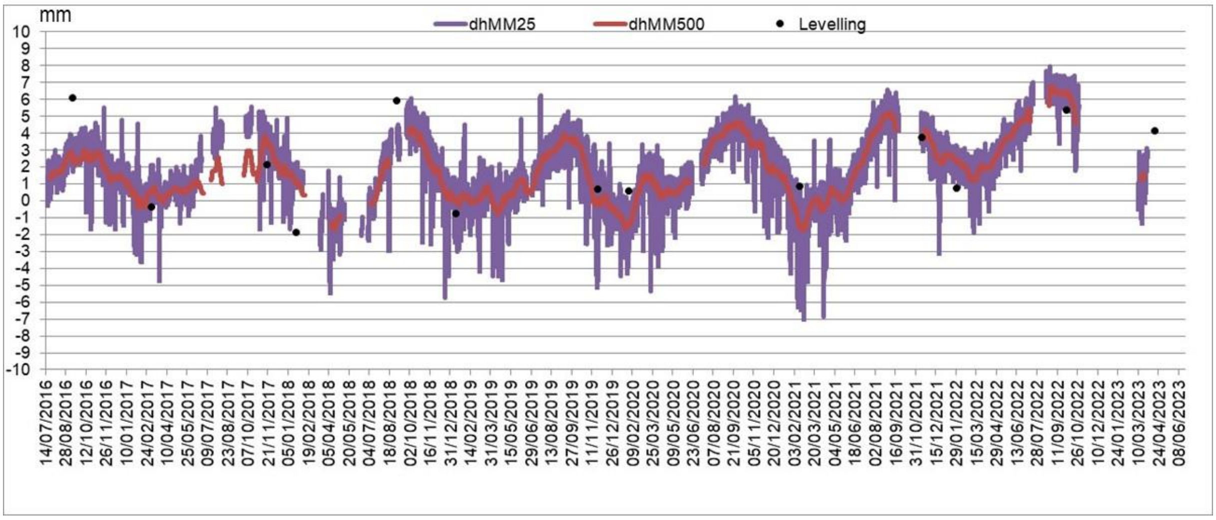

Fig. 11 – The results of the applications of 500th and 25th order moving average to the time series of GNSS observed displacements, vertical components, in block KL station of Cabril dam, plus weekly average temperature and spirit levelling

The comparison is made with the spirit levelling 'corrected' to make the origins of the time series in question compatible. And the numerical results in Table 2 confirm the graphical comparisons expressed in the previous figures.

Table 2 – Differences in vertical displacements observed between GNSS and spirit levelling

Campaign Data	Levelling Observed KL crest	Levelling Corrected KL crest	dh mm25 GNSS	dh mm168 GNSS	dh mm500 GNSS	Difference dhmm25 – Levelling	Difference dhmm168 – Levelling	Difference dhmm500 – Levelling
13/09/2016	12.02	6.02	2.4	2.9	2.6	-3.6	-3.1	-3.4
07/03/2017	5.6	-0.4	1.0	0.8	0.6	1.4	1.2	1.0
21/11/2017	8.07	2.07	3.8	3.6	3.4	1.7	1.5	1.3
23/01/2018	4.1	-1.9	1.6	1.5	1.0	3.5	3.4	2.9
04/09/2018	11.88	5.88	3.9	2.5		-2.0	-3.4	
14/01/2019	5.21	-0.79	0.3	-0.6	0.0	1.1	0.2	0.8
26/11/2019	6.67	0.67	-0.3	-0.9	-0.1	-1.0	-1.6	-0.8
03/02/2020	6.55	0.55	-0.5	-1.5	-1.4	-1.1	-2.1	-2.0
16/02/2021	6.82	0.82	-0.5	-1.3	-1.6	-1.3	-2.1	-2.4
16/11/2021	9.73	3.73	0.6	-0.4	-0.2	-3.1	-4.1	-3.9
31/01/2022	6.71	0.71	2.3	2.5	2.3	1.6	1.8	1.6
03/10/2022	11.34	5.34	6.7	6.4	6.4	1.4	1.1	1.1
Average						**-0.12**	**-0.60**	**-0.35**
Standard Desviation						**2.11**	**2.32**	**2.16**

4.4. Feiticeiro dam

The case of the Feiticeiro dam is a good example because the distance between the reference GNSS station and the GNSS stations on the top of the dam is neither too long nor too short (the average distance is around 360 metres) and, more importantly, the slope between these stations is neither too high nor too low (around 60 metres). The Figure 12 shows the results of applying a 25th order moving average to the time series of GNSS observed displacements, the vertical components, at the FP1, FP2 and FP3 GNSS stations of the Feiticeiro dam (orange, blue and grey dots, respectively) and the spirit levelling observed at the bench marks closest to the GNSS stations (NC0607, yellow dots, NC1112, dark blue dots, and NC1617, black dots).

Figure 13 is an enlargement of Figure 12. Unfortunately, there are few spirit levelling campaigns during the GNSS observation period, so it is not possible to make a good comparison between these two observing techniques, nor to correct for the different origins of the different time series.

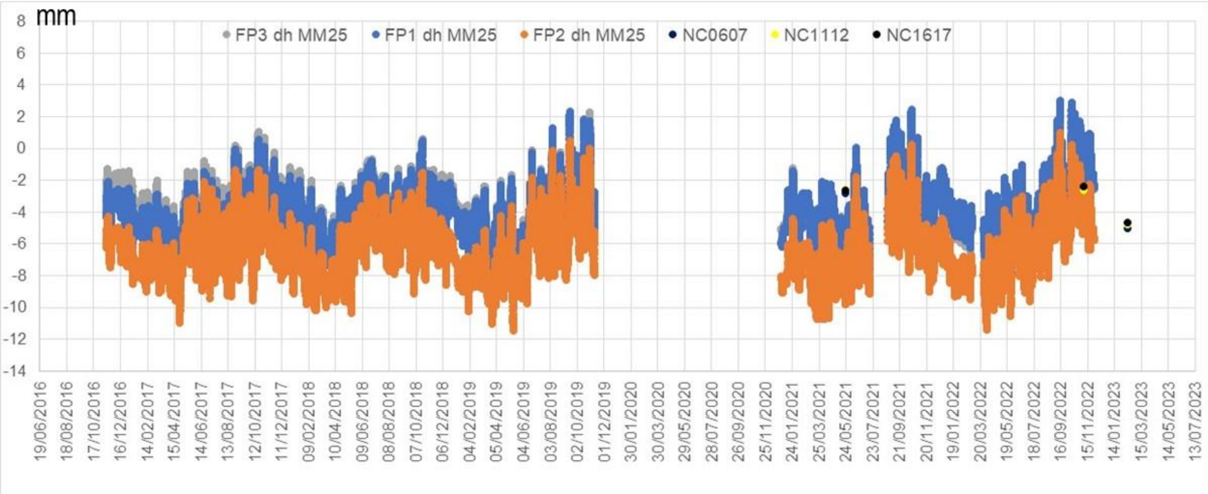

Fig. 12 – The results of applying a 25th order moving average to the time series of GNSS observed displacements, vertical components, in the FP1, FP2 and FP3 GNSS stations of the Feiticeiro dam (orange, blue and grey dots, respectively) and the spirit levelling observed at the benchmarks closest to the GNSS stations

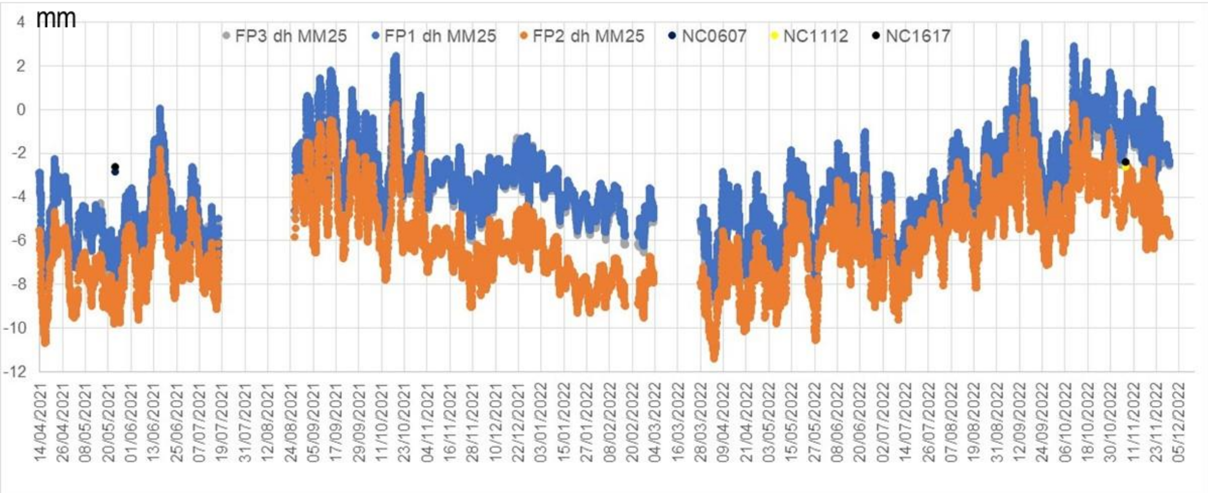

Fig. 13 – Figure 13 is an enlargement of Figure 12: The results of applying a 25th order moving average to the time series of GNSS observed displacements, vertical components, in the FP1, FP2 and FP3 GNSS stations (orange, blue and grey dots, respectively) and the spirit levelling observed at the benchmarks closest to the GNSS stations

Figures 14 and 15 are similar to Figures 12 and 13, except that the 25th order moving average is replaced by the 168th order moving average. The same conventions are used as in the previous figures.

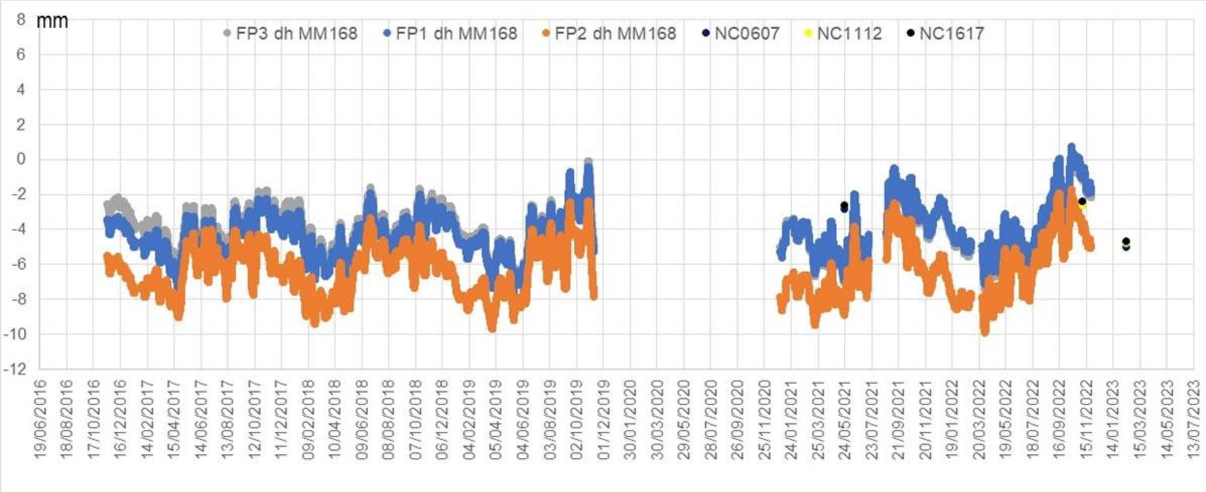

Fig. 14 – The results of applying a 168th order moving average to the time series of GNSS observed displacements, vertical components, in the FP1, FP2 and FP3 GNSS stations of the Feiticeiro dam (orange, blue and grey dots, respectively) and the spirit levelling observed at the benchmarks closest to the GNSS stations

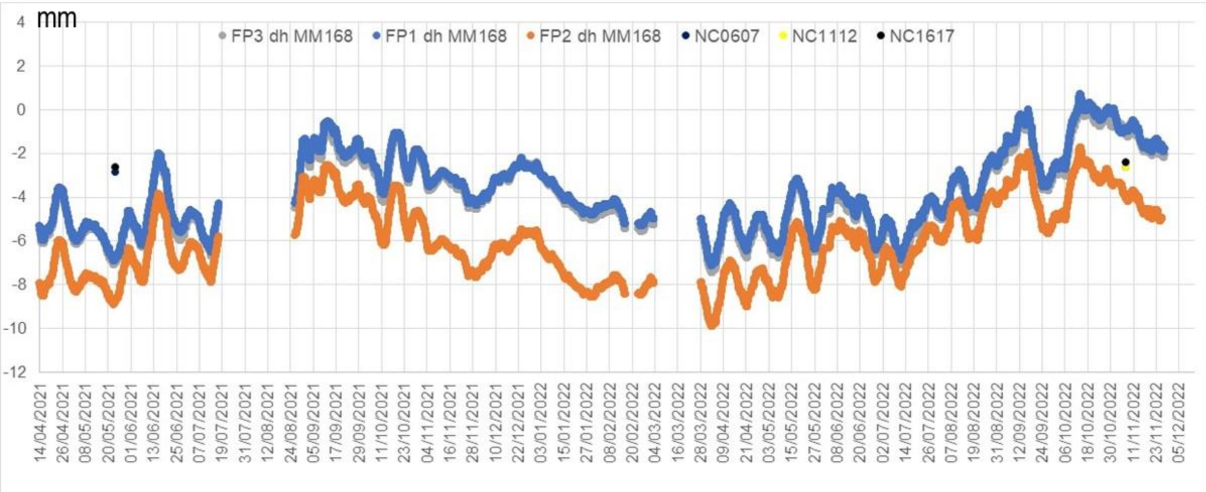

Fig. 15 – Figure 15 is an enlargement of Figure 14: The results of applying a 168th order moving average to the time series of GNSS observed displacements, vertical components, in the FP1, FP2 and FP3 GNSS stations (orange, blue and grey dots, respectively) and the spirit levelling observed at the benchmarks closest to the GNSS stations

Table 3 shows the differences between the height variations observed at the GNSS stations FP1, FP2 and FP3 and the values obtained by spirit levelling at the benchmarks closest to the GNSS stations, NC0607, NC1112 and NC1617, respectively. It should be noted, however, as already mentioned, that unfortunately there were few spirit levelling campaigns during the period under study, which did not allow a good comparison between the results of the two techniques, nor the correction of the different origins of the time series for a more accurate comparison.

Table 3 – Differences in vertical displacements observed between GNSS and spirit levelling

Campaign Data	Difference FP1 dhmm25 – Levelling Observed NC0607	Difference FP2 dhmm25 – Levelling Observed NC1112	Difference FP3 dhmm25 – Levelling Observed NC1617	Difference FP1 dhmm168 – Levelling Observed NC0607	Difference FP2 dhmm168 – Levelling Observed NC1112	Difference FP3 dhmm168 – Levelling Observed NC1617
24/05/2021	3.66	5.78	3.76	3.96	6.08	4.26
07/11/2022	-2.15	0.85	-1.83	-1.75	1.45	-1.23
13/02/2023	-	-	-	-	-	-
Standard Desviation	**4.11**	**3.49**	**3.95**	**4.04**	**3.27**	**3.88**

Figures 13 and 15 show that, in this case, there is no advantage in increasing the order of the moving average to improve the accuracy of the time series of the height variation of the Feiticeiro dam observed by GNSS. And the numerical results in Table 3 confirm the graphical comparisons expressed in the previous figures, which means that there is no advantage in increasing the order of the moving average to improve the accuracy of the time series of the height variation observed by GNSS. Due to the lack of spirit levelling campaigns during the period considered, it is not advisable to use the standard deviation of the differences as an estimate of the accuracy of the GNSS vertical component, as it would clearly be overestimated in this case. In other words, we would expect better accuracy in this component of the GNSS observations. For example, in defence of the statement in the previous sentence, note the consistency of the height variations observed at the three GNSS stations at the top of the dam.

4.5. Foz Tua dam

The Foz Tua dam was only monitored by GNSS during its first filling, between May 2016 and May 2017. During this period, there were not enough spirit levelling campaigns to validate the results of the height component observed by GNSS. The only possible comparison will be with trigonometric levelling using a robotic tacheometer installed in the dam, with hourly frequency observations for different reflector targets placed in the dam, one of which was very close to the GNSS antenna placed on the top of the dam. These comparisons will be analysed.

Like the Feiticeiro dam, the Foz Tua dam is a good example because the distance between the reference GNSS station and the GNSS station at the top of the dam is 242 metres and, more importantly, the gradient between these stations is 80 metres.

In this case there are only daily solutions, i.e. each solution corresponds to a full day of GNSS observations. Figure 16 shows the daily GNSS solution, in the altimetric component, represented in light blue, a moving average of order 7 of this time series (corresponding to the weekly moving average), in dark blue and in red the moving average of order 24 of the hourly solutions, in the altimetric component, observed by the robotic tacheometer.

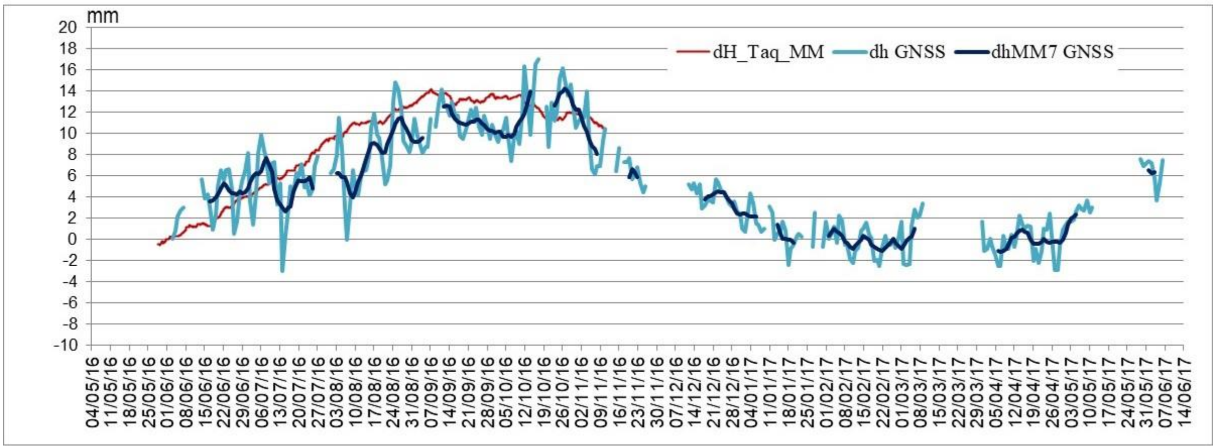

Fig. 16 – the daily GNSS solution, in the altimetric component, represented in light blue, a moving average of order 7 of this time series (corresponding to the weekly moving average), in dark blue and in red the moving average of order 24 of the hourly solutions, in the altimetric component, observed by the robotic tacheometer

The weekly moving average of the GNSS time series is much more consistent with the robotic tacheometer time series than the daily GNSS time series, with standard deviations of the differences for the latter of 3 mm and 5 mm respectively.

4.6. Discussion

The Baixo Sabor, Cabril and Feiticeiro dams are equipped with Leica GMX902 GNSS receivers, Leica AR20 antennas (choke ring antennas for the first and third dams) and Leica AS10 antennas (geodetic quality antenna for the Cabril dam). The software that manages and automatically processes the observations is also from Leica and is called Spider. The Foz Tua dam was equipped with two Topcon GB-1000 receivers with two Topcon Choke Ring antennas. The software that processed these observations was developed by Topcon and is called Pinnacle. The observations were processed manually. Both software programs are commercial and therefore have some limitations compared to scientific software, especially when it comes to processing the tropospheric delay. In other words, it would be possible to obtain better results in the height component by using scientific software, such as Bernese GNSS Software version 5.4 [6].

In general, increasing the order of the moving average in the GNSS observation time series should correspond to an increase in the accuracy of the observation time series. The other side of the coin is that the smoothing introduced may eliminate some important signals.

In the case of the Baixo Sabor dam, the large difference in altimetry between the GNSS stations is an important factor limiting the accuracy achieved in the height component. Only the weekly moving average (order 168) can reduce the uncertainty. On the other hand, for the Cabril and Feiticeiro dams, increasing the order of the time series moving average doesn't seem to bring any advantages. For the Foz Tua dam, where the difference in elevation is 80 metres, we recommend using the weekly moving average. It should be noted that there isn't much difference in the height difference between the GNSS stations at this dam and the Feiticeiro dam (80 metres versus 60 metres). It should also be noted that for the horizontal components, the results in each of these dams are very accurate, regardless of the hardware and software used [3].

5. CONCLUSIONS

High gradients between GNSS stations can significantly limit the accuracy required for dam monitoring, but only in the altimetric component. There is no problem in monitoring dams with GNSS in the horizontal component. Better results would be expected if scientific software were used to process these GNSS observations, especially software that could better model the tropospheric delay.

Table 1 shows that the uncertainty in the vertical displacements observed with GNSS at the Baixo Sabor dam, which in this particular case is strongly influenced by the height differences between the GNSS stations, is too high to monitor a concrete dam. Even with the application of high order moving averages and the progressive smoothing of the observed time series, the corresponding standard deviations are still very high, far from the 1 mm accuracy required for monitoring concrete dams. On the other hand, for the Cabril and Feiticeiro dams, increasing the order of the time series moving average doesn't seem to bring any advantages, where the 25th order moving average seems to be accurate enough to be compared with the spirit levelling time series and to be used for dam monitoring. Although there were few geometric levelling campaigns at the Feiticeiro dam during the study period, this may have affected the comparison and validation of GNSS monitoring of the vertical component.

For the Foz Tua dam, where the difference in elevation is 80 metres, we recommend using the weekly moving average.

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