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QUALITY ASSESSMENT OF GNSS WITH SHORT-LENGTH SESSION IN THE DISPLACEMENT MEASUREMENT OF A LARGE EMBANKMENT DAM

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Abstract. *After a large set of GNSS tests carried out on a 325 m baseline, with different length observation sessions, we assessed the quality of GNSS with short-length sessions to monitoring the displacements of a large embankment dam, in south of Portugal. The GNSS campaigns were performed at the same time of classic geodetic observation campaigns, with Leica TCA2003 tacheometer and Leica NA2 optical level, and the results were compared: the standard deviations of the differences of the two methods for horizontal and vertical displacements were 3.6 mm and 5.7mm, respectively. These values are in agreement with those which we obtained on a 325 m baseline with GNSS using sessions of 5 minutes length. The results of this test show that the GNSS with short-length sessions has enough precision to monitoring large embankment dams.*

1 INTRODUCTION

To test the viability of the GNSS with short-length sessions in the measuring of displacements of large embankment dams, the Division of the Applied Geodesy of the Concrete Dams Department, of the National Civil Engineering Laboratory (LNEC), has carried out several studies in the Portuguese large dams. In the present paper we show the results obtained from the GNSS observations campaigns in Odelouca Dam (Figure 1), February 2010, January 2011, June 2011 and September 2014. These results are horizontal and vertical displacements of seven object-points on the dam crest, previously selected for this study, and are related to the February 2010 campaign, the zero epoch of the monitoring geodetic system.

Precise GNSS relative positioning requires the using of carrier-phase observations, at the least of two receivers, and fixing the integer ambiguities (i.e. the initial phase shift between the receiver and the satellite). With increasing distance between receivers, ambiguity fixing becomes more difficult because ionospheric and tropospheric effects do not cancel sufficiently in double difference (the best combination model for the relative positioning). A most common procedure in static relative positioning is to increase the length of the observation session and/or to apply atmospheric models and corrections. In general, increasing the length of the observation session promotes the decrease of the uncertainty of the displacements measured by the GNSS. In fact, we have carried out several tests in LNEC

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campus, on a 325 meters length GNSS baseline, with different length sessions, from 1 minute to 24 hours, which are proving this statement. Figure 2 present the results obtained: the standard errors for the relative position, in North component (purple balls), East component (blue balls) and height component (orange balls) decrease with the increasing of the session length[1].

Figure 1: The Odelouca Dam (partial views of downstream and upstream)

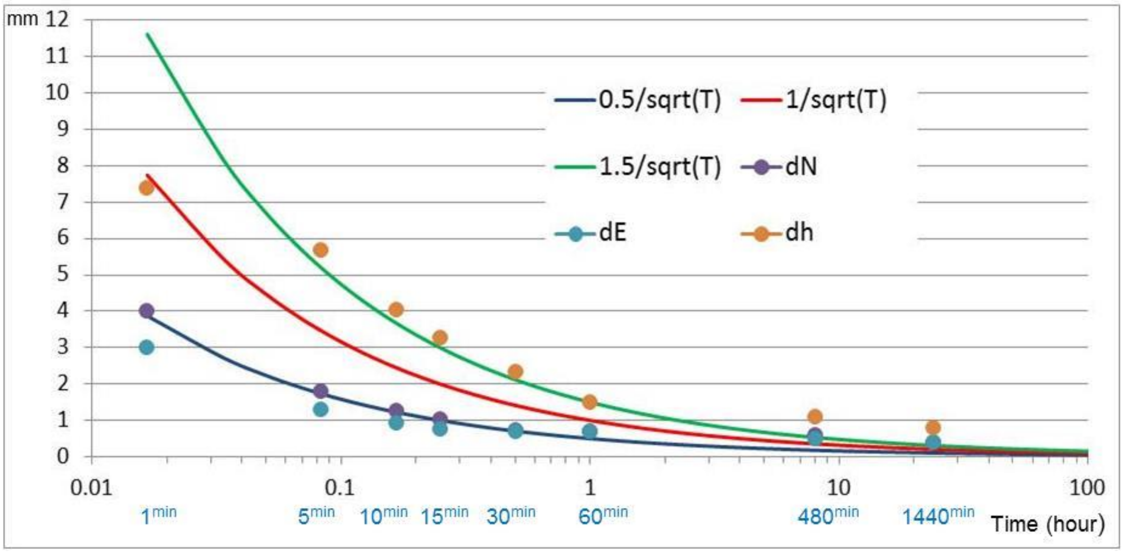


Figure 2: Standard errors for relative position, in N component (purple balls), in E component (blue balls) and in height component (orange balls), on a 325 m GNSS baseline, obtained from 1minute, 5 minute, 10 minute, 15 minute, 30 minute, 1 hour, 8 hour and 24 hour session length.

As shown in Figure 2, the standard error for relative positioning in N component is similar for the E component, but for the height component it is 3 times higher, and they could be expressed by

$$S_N = S_E = \frac{0.5}{\sqrt{T}} mm$$
$$S_h = \frac{1.5}{\sqrt{T}} mm \qquad (1)$$

where S_N, S_E and S_h are the standard errors in N, E and h components respectively, and T is the length session expressed in hour. For example, we obtained for length sessions of 5 minutes the value 1.8 mm for standard error in horizontal component and the value 5.7 mm for standard error in vertical component. With such values for standard errors, a 5 minute observation session it will give us an enough precision for embankment dam displacement monitoring.

2 GNSS CAMPAIGNS AND RESULTS

To take advantage of the surveying monitoring system installed on Odelouca dam, we have carried out GNSS observation campaigns at same time with surveying monitoring campaigns, which it allowed to measured horizontal and vertical displacements of seven object-points on dam crest (orthometric height of 106 m), using two independent methods.

For the GNSS observation campaigns we used two GNSS receivers, TOPCON GB-1000, and two choke ring antennae, TOPCON TPSCR3_GGD (Figure 3). This equipment is for geodetic positioning and it is a dual-frequency receiver for GPS and GLONASS signal satellites. The using of choke ring antennae has considerably reduced the multipath in GNSS observations, mitigating one of the most important errors which affect short-length sessions GNSS positioning.

Figure 3: GNSS Receiver Topcon GB-1000 (left image) and Topcon GNSS Choke Ring antenna TPSCR3_GGD stationed in one of the reference pillars of surveying observation system of Odelouca Dam (right image).

GNSS allows a three-dimensional positioning in a global reference system (e.g. WGS-84, ITRF2008, ETRS89), however these coordinates can be easily converted in to local reference system (associated to a horizontal plane, two of the components are horizontal and the third component is vertical). To facilitate comparison with the displacements obtained with surveying campaigns, the horizontal displacements of the vertical displacements were split up.

Thus, the horizontal displacements obtained with GNSS were compared with those obtained with Leica TCA2003 tacheometer and displacement component in the altimetric GNSS obtained were compared with vertical displacement obtained by the geometric leveling (Leica NA2 optical level).

In all campaigns was followed the same GNSS observation plan: one of GNSS receivers remained stationed in one of the pillars that define the reference frame of the surveying dam system, the PEJ point, while the second receiver was successively stationed at various points : one hour in each of the pillars of the reference frame (PEM1, PDM and PDJ); and for five minutes in each of the selected object-points on the dam crest (1CJ, 3CJ, 7CJ, 9CJ, 11CM, 12CM and 13CM).

The recorded observations in the two receivers were processed in static mode with the Pinnacle, the GNSS software developed by Topcon, resulting from such processing the network of GNSS vectors represented in Figure 4.

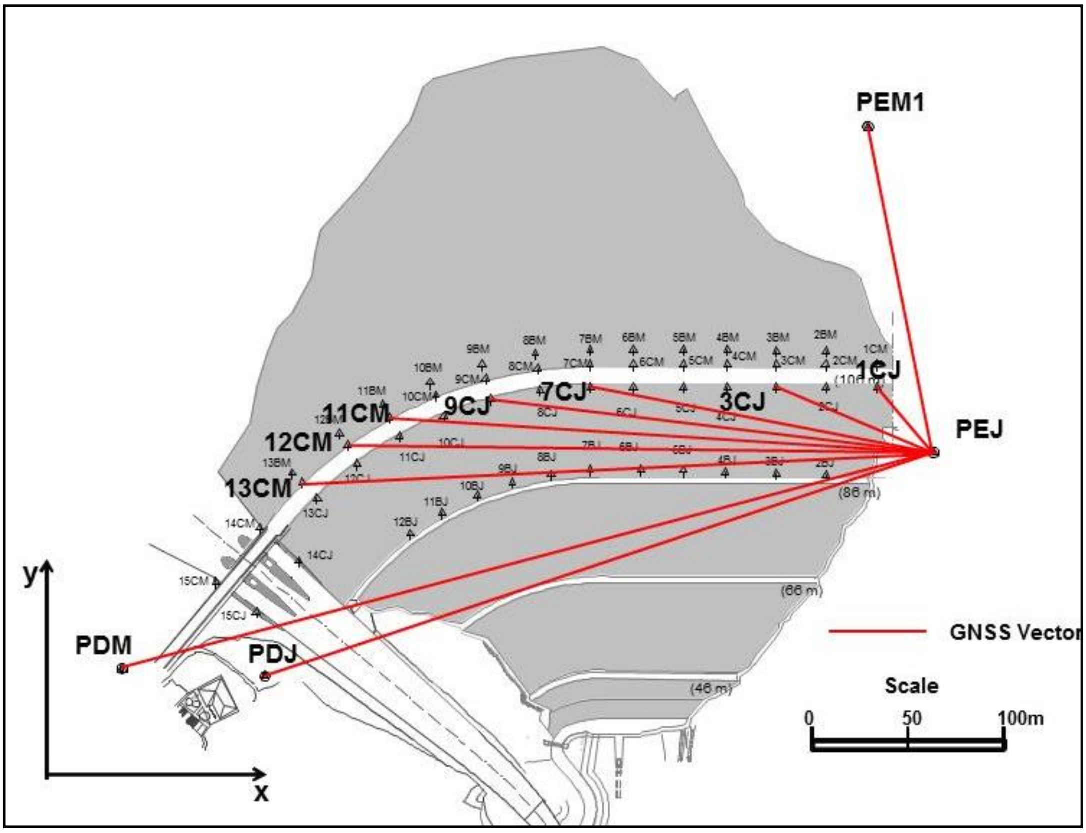


Figure 4: The GNSS network system and the local reference frame of the dam

To minimise errors associated with GNSS absolute positioning, we obtained the coordinates of PEJ in the Portuguese datum PT-TM06[2], from the Lagos GNSS station, which is the nearest station of the National Network of GNSS Permanent Stations (called RENEP). We also used the Pinnacle software for processing the GNSS observations of Lagos station together with the observations recorded in PEJ. Then, fixing the coordinates in PT-TM06 obtained for PEJ and with the GNSS vectors of Odelouca dam we get the coordinates of the remaining points in this datum. Finally, the coordinates of these points were transformed to the local reference frame of the dam. The local reference frame of the dam is defined by a Cartesian reference frame whose y-axis is parallel to the profiles 1-6 of the dam, with positive upstream direction and whose x-axis has positive direction towards the left margin[345] (cf. Figure 4).

2.1 Horizontal displacements

Because the GNSS enables three-dimensional positioning, to determine horizontal and vertical displacement was performed simultaneously (using the same observations and the same observations processing). However, this point shall refer only to the horizontal displacements.

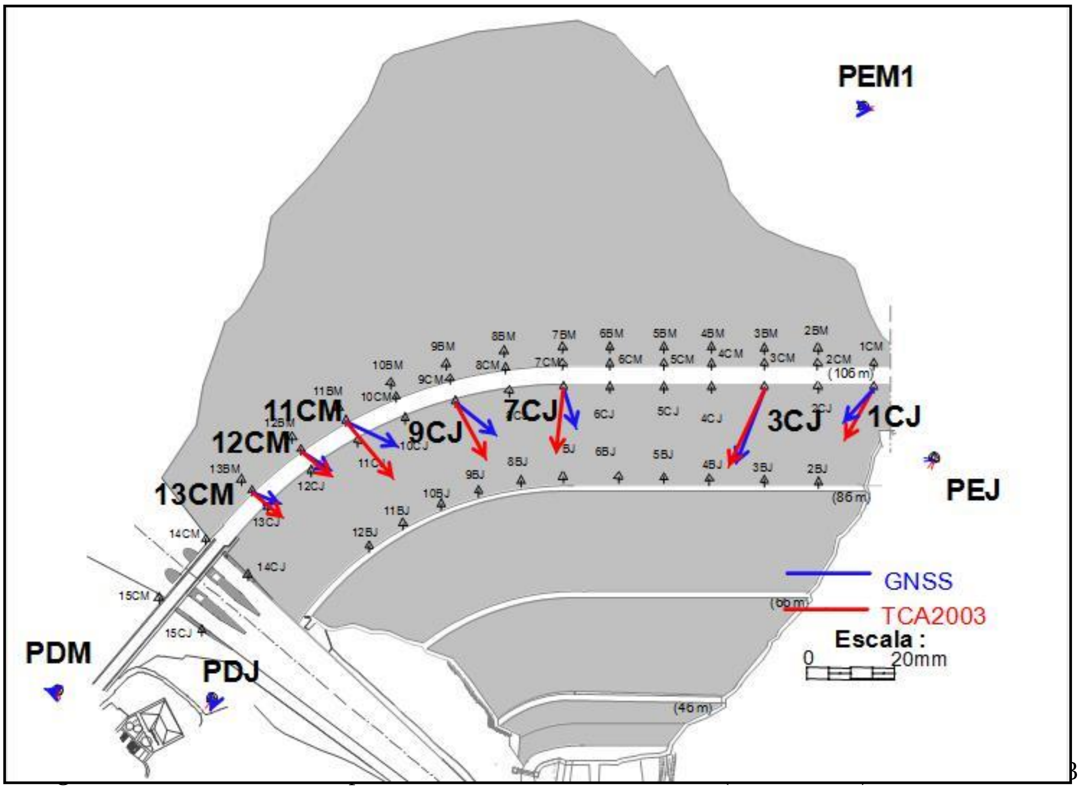
Comparing the coordinates in the local reference frame of the dam obtained from GNSS observations February 2010 and GNSS observations January 2011, resulted in the horizontal displacements between these two periods (Table 1) and, similarly, the horizontal displacements between February 2010 and June 2011 by comparing the coordinates obtained in the respective periods (Table 2), and, finally, horizontal displacements between February 2010 and September 2014 by comparing the coordinates obtained in the respective periods (Table 3).

Tables 2, 3 and 4 present the components (dx, dy) of the horizontal displacements obtained by the two methods (GNSS and Leica TCA 2003 tacheometer) for the local reference frame of the dam. Note that the displacements obtained with tacheometer the coordinates of points that define the frame of reference (PEJ, PDM, PDJ, and PEM1 PEM2) were constrained to the variance of 0,01mm^2. But for the displacements obtained with GNSS only the coordinates of PEJ were considered fixed. In these three tables also present the differences of displacements obtained by the two methods, as well as the statistics associated with these differences.

Object-point	Horizontal Displacements with GNSS (mm)		Horizontal Displacements with TCA2003 (mm)		Difference (mm)	
	dx	dy	dx	Dy	dx	dy
1CJ	-7,1	-8,0	-6,7	-7,7	-0,4	-0,3
3CJ	-6,6	-17,3	-8,4	-13,4	+1,8	-3,9
7CJ	+2,9	-9,2	-1,7	-6,8	+4,6	-2,4
9CJ	+9,4	-7,6	+7,0	-5,3	+2,4	-2,3
11CM	+12,0	-5,7	10,9	-8,2	+1,1	+2,5
12CM	+7,1	-4,6	+7,2	-3,8	-0,1	-0,8
13CM	+6,6	-2,7	+7,2	-2,8	-0,6	+0,1
Mean					+1,3	-1,0
Standard Deviation					1,9	2,1

Table 1: The horizontal displacements of the observed points with GNSS, between February 2010 and January 2011 and their comparisons with the displacements obtained with tacheometer TCA2003.

In Figure 5 are represented the horizontal displacements of the seven object-points on the dam crest observed with the two independent methods, between February 2010 and January 2011. In turn, the Figure 6 also are represented the horizontal displacements at the same points, but now referring to times February 2010 and June 2011. Finally, in the Figure 7 are represented the horizontal displacements at same object-points between February 2010 and September 2014.



tacheometer (red arrows), between February 2010 and January 2011.

Object-point	Horizontal Displacements with GNSS (mm)		Horizontal Displacements with TCA2003 (mm)		Difference (mm)	
	Dx	Dy	dx	dy	dx	dy
1CJ	-5.8	-14.1	-6.7	-11.7	+0.9	-2.4
3CJ	-5.7	-20.2	-3.9	-17.6	-1.8	-2.6
7CJ	+2.7	-13.4	+0.8	-14.5	+1.9	+1.1
9CJ	+10.1	-14.8	+8.9	-13.3	+1.2	-1.5
11CM	+13.5	-7.9	+14.2	-12.5	-0.7	+4.6
12CM	+11.3	-7.0	+11.3	-6.3	0.0	-0.7
13CM	+6.9	-5.7	+11.3	-5.8	-4.4	+0.1
				Mean	-0.4	-0.2
				Standard Deviation	2.1	2.5

Table 2: The horizontal displacements of the observed points with GNSS, between February 2010 and June 2011 and their comparisons with the displacements obtained with tacheometer TCA2003.

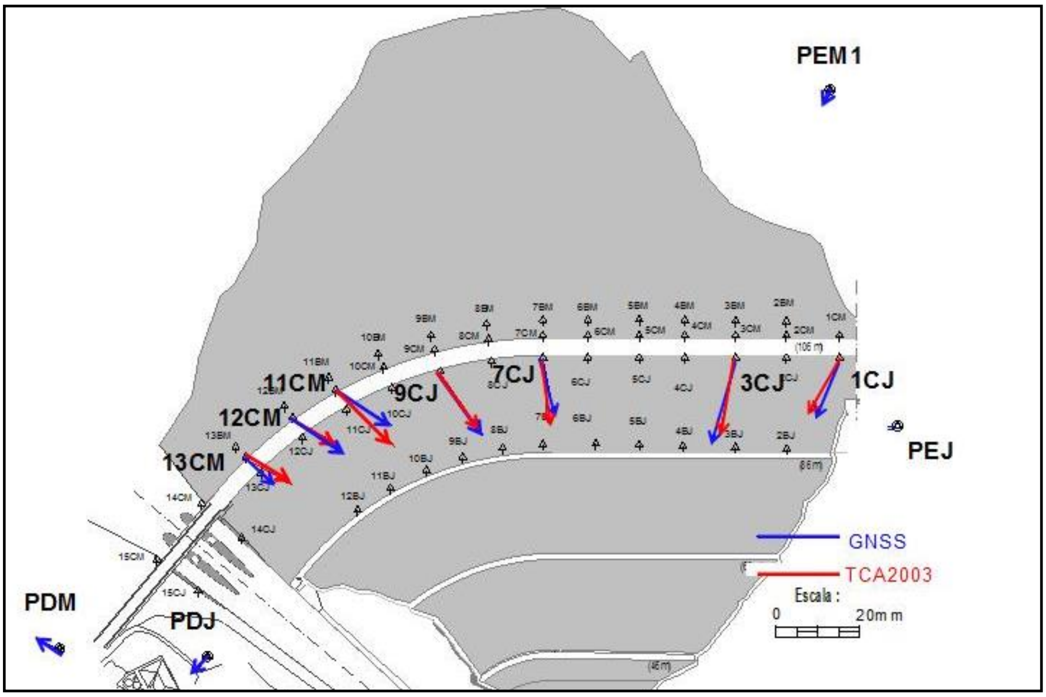


Figure 6: The horizontal displacements obtained with GNSS (blue arrows) and the TCA2003 tacheometer (red arrows), between February 2010 and June 2011.

Object-point	Horizontal Displacements with GNSS (mm)		Horizontal Displacements with TCA2003 (mm)		Difference (mm)	
	Dx	dy	dx	dy	dx	Dy
1CJ	-6.6	-38.3	-7.9	-39.4	-1.3	-1.1
3CJ	+4.1	-54.5	+0.8	-54.4	-3.3	+0.1
7CJ	+10.3	-48.6	+2.7	-45.9	-7.6	+2.7
9CJ	+25.2	-41.1	+22.3	-40.0	-2.9	+1.1
11CM	+29.1	-21.6	+27.3	-30.9	-1.8	-9.3
12CM	+25.3	-14.1	+24.7	-15.9	-0.6	-1.8
13CM	+21.3	-12.2	+21.5	-12.6	+0.2	-0.4
Mean					-2.5	-1.2
Standard Deviation					+2.4	+3.6

Table 3: The horizontal displacements of the observed points with GNSS, between February 2010 and September 2014 and their comparisons with the displacements obtained with TCA2003 tacheometer.

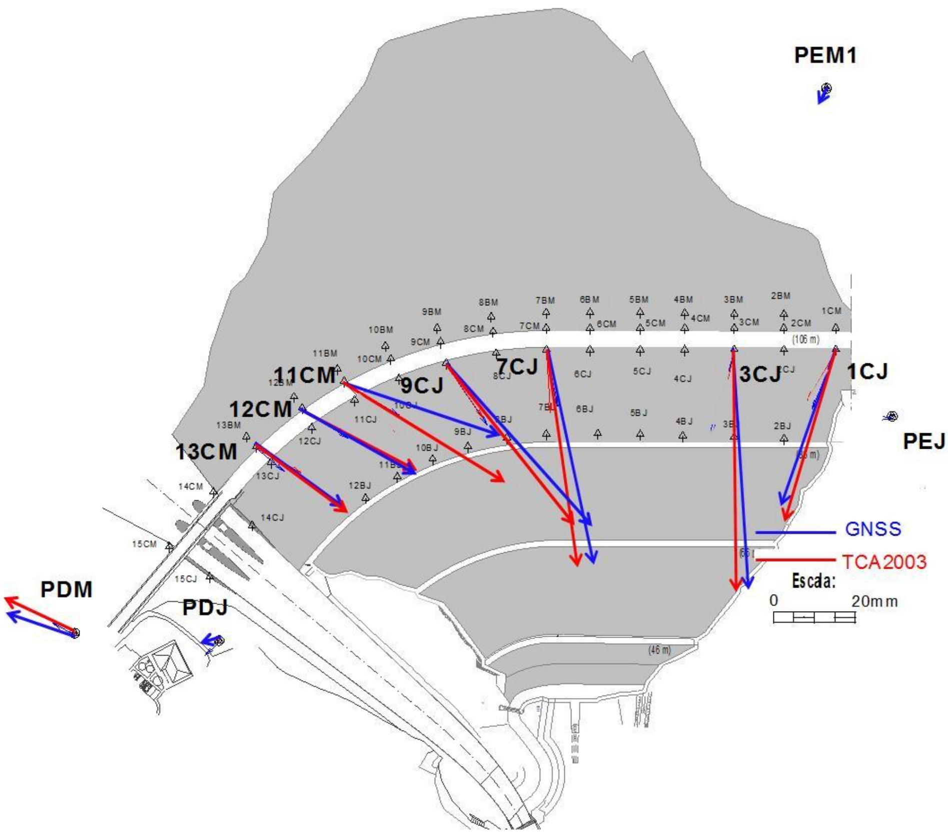


Figure 7: The horizontal displacements obtained with GNSS (blue arrows) and the TCA2003 tacheometer (red arrows), between February 2010 and September 2014.

2.2 Vertical displacements

The determination of vertical displacements (variation of height or the altitudes of points between two epochs) in Odelouca dam is carried out by geometric leveling with the exception of points within the upstream, whose vertical displacements are determined by trigonometric leveling, once that there are no conditions for the realization of geometric leveling[345].

The vertical movements refer to axes with the vertical direction of each point in the positive direction and directed toward the zenith: points with positive vertical displacement means uplift and points with negative vertical displacement show subsidence. In the case of GNSS, the vertical displacements are obtained from ellipsoidal height changes in each campaign. Although the ellipsoidal height of a point is defined by the normal to the ellipsoid at that point, locally varying the ellipsoidal height is equal in value to the variation of orthometric height. In Table 4 we compare the variations of the ellipsoidal heights (dh) measured by GNSS with variations of orthometric heights (dH) obtained by geometric leveling between February 2010 and January 2011 (2^{nd} to 4^{th} column), between February 2010 and June 2011(5^{th} to 7^{th} columns), and between February 2010 and September 2014 (8^{th} to 10^{th} columns).

In Figure 8 we compare the vertical displacements measured by the two methods, geometric leveling and GNSS, between the epochs January 2011 and February 2010, between June 2011 and February 2010, and between September 2014 and February 2010.

The comparison is possible only for seven object-points in the dam crest where the displacements were observed by both methods. To determine the vertical displacements with GNSS, we fixed the ellipsoidal height of the reference point PEJ. However, the line of geometric leveling in dam crest was fixed on four outer references to the dam, two on each bank.

Object-point	Displ GNSS (mm)	Displ levelling (mm)	Differ (mm)	Displ GNSS (mm)	Displ levelling (mm)	Differ (mm)	Displ GNSS (mm)	Displ levelling (mm)	Differ (mm)
	dh (2011a)	dH (2011a)	dh – dH	dh (2011b)	dH (2011b)	dh – dH	dh (2014)	dH (2014)	dh – dH
1CJ	-12.8	-11.8	-1,0	-12.2	-16.0	+3.8	-50.41	-47.2	+3.2
3CJ	-39.0	-39.6	+0,6	-48.3	-49.9	+1.6	-112.75	-110.0	+2.7
7CJ	-63.0	-65.2	+2,2	-80.0	-80.5	+0.5	-157.18	-168.6	-11.4
9CJ	-50.4	-51.5	+1,1	-68.3	-66.4	-1.9	-134.44	-140.5	-6.0
11CM	-24.6	-21.4	-3,2	-32.2	-28.1	-4.1	-52.95	-55.1	-2.2
12CM	-19.6	-15.6	-4,0	-19.2	-21.3	+2.1	-33.46	-42.9	-9.4
13CM	-11.5	-14.1	+2,6	-21.1	-19.3	-1.8	-43.24	-41.1	+2.2
		Mean	-0.2		**Mean**	+0,0		**Mean**	-3.0
		Standard Deviation	2.6		**Standard Deviation**	2.6		**Standard Deviation**	5.6

Table 4: The vertical displacements of object-points observed with GNSS, between February 2010 and January 2011, February 2010 and June 2011 and February 2010 and September 2014, and their comparisons with the displacements obtained with the leveling.

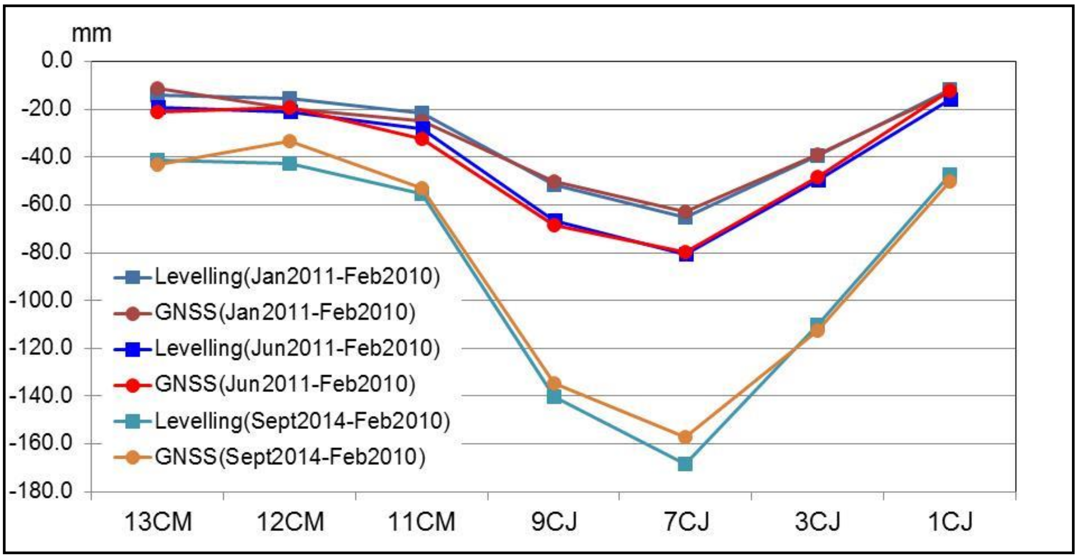


Figure 8: Comparison of vertical displacements obtained by geometric leveling and GNSS, between the epochs January 2011 and February 2010, between June 2011 and February 2010, and between September 2014 and February 2010.

3 DISCUSSION OF THE RESULTS

The results show that GNSS may be an expeditious technique for precise measuring the horizontal and vertical displacements of an embankment dam. In fact, comparing the horizontal displacements obtained with GNSS with the displacements measured with tacheometer TCA2003 are obtained standard deviations between 1.9mm and 3.6mm. Similarly, when comparing the vertical displacements obtained with GNSS with the measured vertical displacement with the leveling is obtained standard deviations of less than 5.6mm.

The observation with GNSS is simpler than the classical topographic observation, requires, however, the same careful centering and leveling of bases and also to accurately measure the heights of the GPS antenna in relation to references - not dispensing, therefore, a specialized and experienced team for observation. And requires the use of geodetic precision equipment and is recommended to use type antennas Choke Ring.

Although the expeditious observation with GNSS can be more time consuming than the classical topographic observation (observation with tacheometer more leveling) benefits from important advantage of being made under any weather conditions and at any time of day (it is not necessary to observe in times of lower atmospheric refraction). The GNSS observation will become even more competitive with the use of more equipment to record simultaneously. For example, with a third GNSS (one fixed and two rovers) observing at the same time the work is reduced to half the time. And so on.

Tests carried out in LNEC[1] show that increasing the duration of the observing session with GNSS levels of uncertainty decreases (cf. Figure 2). The best results were obtained when the GNSS stations operate in continuous mode (permanent stations).

The comparison of the results shows values of 3.6 mm and 5.7mm for standard deviation of the differences of the two methods for horizontal and vertical displacements respectively. These values are in agreement with those which we obtained on a 325 m baseline with GNSS using sessions of 5 minutes length. The results of this test show that the GNSS with short-length sessions has enough precision to monitoring large embankment dams.

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