Evaluation of the sensitivity of 3D monitoring networks by applying both different measurement methods and adjustments

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Abstract. The aim of this work is the evaluation of a monitoring network depending on the measurement method and the data processing methodology.

The sensitivity of a monitoring network is a crucial parameter as it influences the magnitude of the displacement which can be detected for a concrete confidence level. The construction and placement of the network points is very important in order to facilitate forced centering and efficient surveying instrument setup. Also ensures the ease and the quickness of the measurements.

This research is carried out by using a prototype monitoring network, which was established on 2012 at the plant of Electricity Authority of Cyprus in Vassilikos.

At first the construction of the network's pillars is described in detail. Also the design and establishment time required is referred. Additionally the cost of the network is criticized as well as the difficulties of the process and possible missteps are presented.

The network was measured both by using GNSS receivers and first order total station. Four separate adjustments of the network were carried out. These adjustments include the GNSS measurements and the terrestrial measurements in 1D, 2D and 3D. The results, namely the points' coordinates and their uncertainties are compared to each other in order to bring forth the best procedure, which provides simultaneously the minimum errors and which requires the minimum effort.

The goal is the improvement of the procedure as well as the detection of the elements which increase the uncertainty of the network's results.

Keywords. 3D monitoring networks, sensitivity, GNSS measurements, Total station, Terrestrial measurements, implementation, GIS

1 Introduction

The fast technology evolution the last two decades leads to the formation of modern special constructions such as metallic buildings, bridges, high buildings, oil reservoirs etc. On parallel high-end geodetic networks are established at the site around these constructions aiming the support of the setting out procedure and thereinafter their monitoring. Such networks have been established for dam's (Lienhart W. Et al (2013)), volcanos' (Yu T. et al (2000)), (Darby D. Et al (2000)) monitoring or ground surface response to resource extraction (Garthwaite M. Et al (2015)).

The most important parameters are the choice of the appropriate positions for the points' installation (Grafarend E. Sansò F. (2012)) and the implementation means in order to facilitate forced centering and efficient surveying instrument setup. Diachronically several techniques have been applied taking into account the geomorphologic conditions of the surround area. Usually concrete pillars (Brown N. et al (2004), Temenos C. (2007)) or specially marked wells embedded in the ground (Garthwaite M. Et al (2015)) or portable metallic pillars (Lambrou et al (2011)) were established.

Also another main parameter concern the data analysis and adjustment methodology as either terrestrial measurements by using Robotic total station or GNSS measurements were carried out separately or simultaneously (Brown N. et al (2004), Ghilani C.Wolf P. (2006)).

The sensitivity of a geodetic network is a crucial parameter as it defines the capacity to detect and measure movements and deformations in the area covered by the network (Even-Tzur G., (2010), Yu T. et al (2000)).

Also the information and the results concern the infrastructure and monitoring geodetic networks are organized on databases for the service the diffusion be easier and safe.

This work presents the complete implementation procedure, the measurements, adjustments and data analysis but also the organization of all the collected data of a geodetic monitoring network, which established at Vasilikos Power Station of Electricity Authority of Cyprus (EAC).

2 Design and network establishment

Vasilikos Power Station of Electricity Authority of Cyprus (EAC) suffered severe damages after an explosion in 2011 in the nearby military base. Therefore the main aim of the establishment of a monitoring network at the Vasilikos Power Station is to provide the means for high precision measurements for all construction works carried out in the reconstruction of the Power Station. Furthermore the monitoring network will facilitate the monitoring over time of the four steel chimneys and the one 130m height reinforced concrete chimney. In addition to the above the network will facilitate the monitoring of the deformation of a 30m height artificial declivity in the west site of the Vasilikos plot.

The whole procedure for the network establishment consists of the following five steps. At first the location of the best suited sites to place the control points must be made starting with the main, fixed control point location.

The second step is to decide what type of pillar to place at each location (precast pillar, steel structure, special construction), then design each pillar and all pillars' components.

The third step is to manufacture everything, from steel components to precast pillars. Make all necessary site preparation, foundation excavation and bedding at each control point location.

The fourth step was the positioning of each pillar to its final place, do a proper backfill and distinctively mark them.

Finally take measurements with GNSS and Total Station and analyze the data.

After a number of site inspections, it was decided that a total number of 8 control points will enable the network to meet the above requirements (figure 1). The main problems encountered on site were: there are too many industrial type structures within the site that obscure line of sight between control points, too much non-moving heavy machinery, mainly the 4 power generators, that provide too many vibrations and most probably will cause nearby locations to oscillate. Another issue we faced was that almost all structures are made of steel, something that has been bothering us as GNSS signal bounces on steel structures inducing errors in the measurements due to multiple signal paths.

Figure 1 Plan of the network as designed and implemented depicting the control points

The main, fixed control point location was selected to be on a reinforced concrete structure to the north part of the main construction site and at distance about 600m from the power generators. This location was chosen as it is free of any vibrations and is a monolithic structure with very deep foundation that rests on a stable geologically formation that guaranties the stability of the point for now and in the future.

Figure 2 The formation of the pillars

The other 7 control points, as presented in Figure 2, were placed at location that satisfy a list of criteria including but not limited to: uncompromised sky visibility, best possible geometry between all control points in the network, undisturbed line of sight between the minimum number of control points, accessible by personnel for measurements using both GNSS receivers and Total Station, etc (Constantinidis C. (2013))

3 Measurement and adjustment by using GNSS Receivers

The measurements were carried out in two distinct phases in order to eliminate the satellite geometry error influence. Two models of GNSS receivers, Leica GS15 and Leica GX1230GG were used, both models provide dual frequency support. Phase 1 took place on August 13 using 8 GNSS receivers as Phase 2 took place on November 6. The duration of the measurements at each point was 7.5 hours. All measurements were made applying the static positioning method.

Special care was given in order to measure the receiver antenna height as any error in the antenna height measurement is a main source for errors in the network adjustment. The antenna height was measured using a Leica digital level and a special method which is proposed by Lambrou E. 2013 providing accuracy of ±0.3mm.

The software used for the network adjustment is Leica GeoOffice 8 (LGO). The mean values of the coordinates of the control points were calculated at a local reference system by the two phases. Also the corresponding uncertainty for each coordinates as no-equal weight observations according to the uncertainty of each phase.

Table 1 presents the results (Constantinidis C. (2013)).

Table 1 GNSS network adjustment

Control Point	x (m)	σx (mm)	y (m)	σy (mm)	H (m)	σH (mm)
1-Submarine	5000	-	5000	-	35.504	-
2-Parking	5040.359	±0.6	4381.521	±0.4	11.059	±0.7
3-Thalassa	5125.491	±1.2	4169.480	±0.6	9.970	±1.6
4-Skopia	4613.533	±1.0	4332.7068	±0.9	41.516	±2.8
5-Kratiras	4627.077	±0.3	4559.924	±0.2	63.238	±0.3
6-Pefka	4614.189	±2.2	4709.373	±0.9	61.947	±0.4
7-DayTank	4750.943	±0.9	4597.542	±2.2	24.512	±3.0
8-Pumphouse	4955.155	±1.1	4596.951	±1.8	24.436	±0.5

4 Measurement and adjustment by using Total Station

Due to the location of Power Station, close to the seaside, a major issue was the weather conditions on site during the measurements phase. Nearly all baselines are more than 500m that demands nearly ideal weather conditions in order to locate the target through the telescope and minimize the effect on the measurement's error. In the morning time (until 10:00), the rate of increase of the ambient temperature was steep resulting to major evaporation of the mist on the ground making hard for the observer to locate and lock the target through the telescope. Between 10:00 and 16:00 the heat, humidity and sun were unbearable for the personnel. The best time to take measurements was after 16:00 until late at night. During that period the rate of change of the ambient temperature and the humidity were low making the measurement more bearable and less error prone.

Special care was given to the methodology of measuring the Total Station height by using digital level as it is described in Lambrou E. Pantazis G. 2010 and Lambrou E. Pantazis G. 2015, where the achieved uncertainty of the instrument height reaches ±0.3mm.

As mentioned in section 3 above, the uncertainty in the instrument height is a major source for errors in the 3D network adjustment process increasing the uncertainty of the results.

All measurements were carried out using the total station Leica TCR1202+, which measures angles by accuracy of ±2″ and distances by ±1mm ± 1.5ppm. Also 32 man-hours by the same observer were required in 6 site visits.

Three separate 1D, 2D and 3D network adjustments was carried out in order to detect differences between the coordinate's values and to find out where the maximum accuracies succeeded. The point 1 was considered stable in all adjustments. The tables 2, 3 and 4 present the adjustments results respectively (Stavrou G. (2013).)

Table 2 1D network adjustment results

Control Point	H(m)	σH (mm)
1	35.504	-
2	11.067	±2.7
3	9.976	±2.8
4	41.521	±2.5
5	63.246	±2.0
6	61.953	±2.3
7	24.517	±2.6
8	24.446	±2.2

Table 3 2D network adjustment results

Control Point	x (m)	y (m)	σx(mm)	σy(mm)
1	5000.000	5000.000	-	-
2	5040.360	4381.518	±1.0	±1.0
3	5125.492	4169.481	±1.3	±1.1
4	4613.535	4332.706	±1.0	±1.2
5	4627.075	4559.924	±0.7	±0.7
6	4614.183	4709.375	±0.8	±0.8
7	4750.942	4597.537	±0.6	±0.7
8	4955.158	4596.946	±0.7	±0.9

Table 4 3D network adjustment results

Control Point	x (m)	Y (m)	H (m)	σx (mm)	σy (mm)	σH (mm)
1	5000.000	5000.000	35.504	-	-	-
2	5040.36	4381.516	11.066	±1.1	±0.9	±2.8
3	5125.494	4169.475	9.976	±1.1	±1.1	±3.0
4	4613.534	4332.707	41.526	±1.1	±1.2	±2.7
5	4627.077	4559.927	63.242	±0.8	±1.0	±2.4
6	4614.189	4709.377	61.951	±0.9	±1.1	±2.5
7	4750.945	4597.539	24.513	±0.9	±0.9	±2.5
8	4955.158	4596.946	24.443	±0.8	±0.8	±2.4

5 Discussion on comparisons

The standard error of the coordinates x and y in the 2D and 3D terrestrial adjustment doesn't exceeded ±1.3mm that means that the sensitivity of the network is of the order of ±3mm for confidence level 95%. On the other hand the GPS solution achieves a max standard error of ±2.2mm, which allows for deformation or displacement detection of the order of ±5mm for confidence level 95%.

It can be said that for a high precision monitoring network, when the prospective deformations are few mm, the measurements is better to be made by Total Station.

The height information has a standard error, which reaches the ±3mm in both 1D and 3D terrestrial measurements. This is justified by the refraction coefficient influence to the measurements in those difficult environmental conditions as mentioned in section 4. Also at the same order is the σ_H by GPS solution, where it is well known that height is always less accurate than the x and y coordinates. Thus the sensitivity of the network at the H component is reduced, as there is the possibility to find out displacements more than ±6mm. The comparison calculates the difference between the coordinates values of each point, which come out from each adjustment and it compares this difference with the expected standard error of the difference for confidence level 95%. Namely

$\Delta H_i = H_{i(3D)} - H_{i(1D)}$ and $\sigma_{\Delta H_i} = \sqrt{\sigma^2_{H_{i(3D)}} + \sigma^2_{H_{i(1D)}}}$

Accepted when $\Delta Hi < 1.96 * \sigma_{\Delta Hi}$

where i = the network point 2 to 8

Table 5 Difference between H1D, H3Dthe comparison, the check and the quality of agreement of the results between the control points in height (H) derived from the 1D, 3D terrestrial networks and the GPS adjustments.

Table 5 Difference between H_{1D}, H_{3D} and H_{GPS}

Control Point	$H_{1D} - H_{3D}$ (mm)	$\sigma_{H1D-H3D}$*1.96% (mm)	Pass	$H_{1D} - H_{GPS}$ (mm)	$\sigma_{H1D-HGPS}$*1.96% (mm)	Pass	$H_{3D} - H_{GPS}$ (mm)	$\sigma_{H3D-HGPS}$*1.96% (mm)	Pass
2	1	±8	✓	8	±5	(-)	7	±6	(-)
3	0	±8	✓	6	±6	(-)	6	±6	(-)
4	-5	±8	✓	5	±5	(-)	10	±6	(-)
5	4	±8	✓	8	±4	(-)	4	±5	✓
6	2	±8	✓	6	±4	(-)	4	±5	✓
7	4	±8	✓	5	±5	(-)	1	±5	✓
8	3	±8	✓	10	±4	(-)	7	±5	(-)

Figure 3 presents the percentages of agreement between the H coordinate in all the combinations of the adjustments.

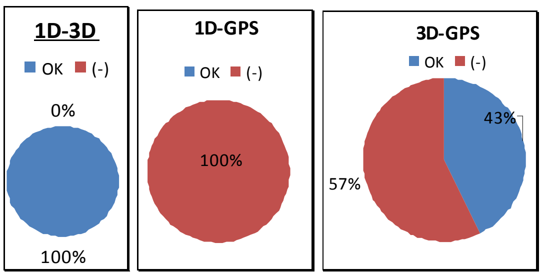

Figure 3 Percentage of agreement between the adjustments for the height

As it is illustrated in table 5, differences between 5mm to 10mm for the H component are observed between the terrestrial and GPS measurements. However, the values of the H component for the terrestrial measurements 1D and 3D are in agreement.

These large differences, which exceed the permissible ones, prohibit mixing up the data in a joint adjustment as they aren’t compatible to each other.

Table 6 Summary of coordinates differences

Control Point	$\Delta_{(2D-3D)}$ Δx	σ Δx *1.96%	Δy	σ Δy *1.96%	$\Delta_{(2D-GPS)}$ Δx	σ Δx *1.96%	Δy	σ Δy *1.96%	$\Delta_{(3D-GPS)}$ Δx	σ Δx *1.96%	Δy	σ Δy *1.96%
	(mm)								(mm)			
2	0	±2	2	±3	1	±2	-3	±2	1	±1	-5	±2
3	-2	±3	6	±3	1	±4	1	±3	3	±3	-5	±3
4	1	±3	-1	±3	2	±3	-2	±3	1	±3	-1	±3
5	-2	±2	-3	±2	-2	±2	-1	±2	0	±2	2	±2
6	-6	±2	-2	±3	-8	±6	3	±2	-2	±5	5	±3
7	-3	±2	-2	±2	-1	±2	-6	±5	2	±3	-5	±5
8	0	±2	0	±2	4	±3	-6	±4	4	±3	-6	±4

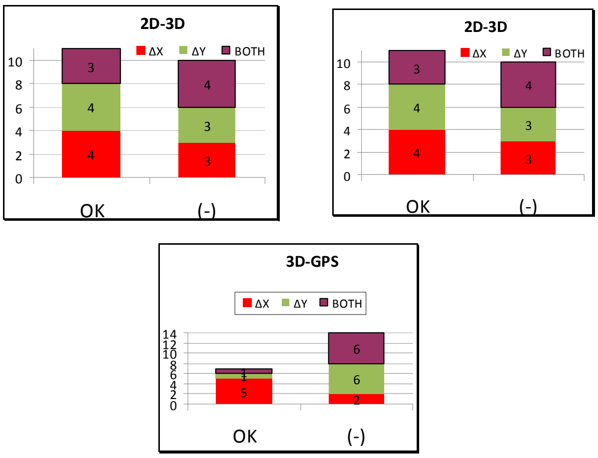

Figure 4 Percentage of agreement between the adjustments for x, y coordinates

The same comparison was carried out for the differences in x and y components derived from network adjustments in 2D Vs 3D, 2D Vs GPS and 3D Vs GPS. The results are summarized in table 6.
Figure 4 presents the percentages of agreement of separate x, y coordinates and also both of them in all the combinations of the adjustments.
As the standard errors of the coordinates’ determination are about ±1mm, there are divergences from 2mm to 8mm for the most of them. Mainly between the terrestrial 3D and GPS measurements there are differences, which exceed the permissible limit for all points, except point 4.
A major issue is emerged about the adjustments’ credibility as the design and establishment of the network fulfills high standard requirements there are no other parameter of the measurement procedure which justified these differences.

6 GIS data base creation

All data and analysis results were stored in a properly designed geodata base that has been developed for this purpose. Two end user applications were developed, one for the surveyors of Electricity Authority of Cyprus, who are considered heavy editors / analysts, with advanced requirements, and one intra-web application for viewing only that serves mainly the needs of contractors at the Vassiliko site.

The software used is ESRI’s ArcGIS desktop 9.3.1 for the desktop application (fig 5) and ArcGIS for Server 9.3.1 for the web application (fig 6). Both, geodatabase schema and the end user application design, are enabled to store all current results as well as any future measurements data and results.

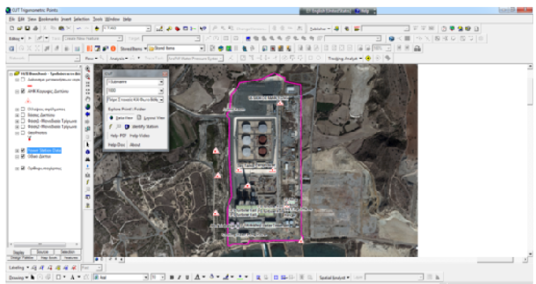

Figure 5 Desktop Application GUI in ArcGIS 9.3.1

The main benefit is that since these are in-house applications, the design can always be adjusted and expanded to meet new requirements.

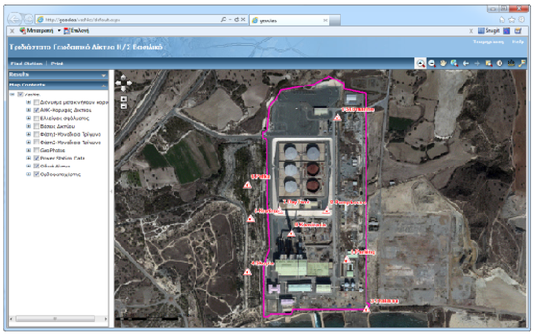

Figure 6 Web Application (.net) served by ArcGIS Server 9.3.1

7 Conclusions

The pillar construction, the forced centering of instrumentation, the procedure for instrument's height measurement and extra care during the measurement phase guaranties results with the lowest uncertainty possible.

Control points location selection and also the design and implementation of all components for the pillars were of major importance due to eliminating errors that could propagate into the measurements.

The different adjustments comparison show that there are significant differences 5mm to 10mm at the height determination between terrestrial and GNSS measurements as the accuracy is of the same order ±2mm to ±3mm.

Also differences between the values of x and y components are observed which fluctuate from 3mm to 8mm, as their standard errors is of the order of ±1mm .Thus the differences exceeded their standard error for confidence level 95%.

Terrestrial measurements leads to more sensitive networks achieving the detection of displacements of ±2.5mm (95%) as the corresponding GNSS network reaches the double traceable value of the order of ±5mm (95%).

Additionally it must be underlined that the GNSS network was measured twice for about 7 hours continuously and so there are a huge observations number, which eliminates the standard errors of the coordinates at a probably unrealistic level. Thus most of the GNSS coordinates aren't in agreement with the corresponding terrestrial ones according to the achieved accuracies.

For monitoring purpose isn't worth to mix up terrestrial and GNSS measurements as there are significant differences of the cm level at the calculated values of all three components x, y and H and this will lead to uncertain conclusions.

However the terrestrial procedure allows better accuracies and the maximum sensitivity.

The creation of the GIS system for all date and results storage is a valuable tool for now and then in order to save, preserve and monitoring the movement behavior of Vassilicos power station area in time.

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