Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

NEW MONITORING TECHNIQUES ON THE DETERMINATION OF STRUCTURE DEFORMATIONS

D.Stathas, O.Arabatzi , S.Dogouris , G.Piniotis , D.Tsini and D.Tsinis

Laboratory of General Geodesy - School of Rural & Surveying Engineering N.T.U.A.
Athens, Greece

Abstract

During the 1999 earthquake in Athens and the vibrations caused by the excavation procedure for the Athens' subway construction, structure deformations occurred. The latter gave rise to the need for building-monitoring in order to assess their structural behavior. Usually, it is impossible to use geodetic targets (or any kind of target) to define the control points on the structure due to the hardly accessible, and sometimes of hazardous nature, measurement environments. Whilst most monitoring work is undertaken using intersection techniques, the application of laser technology to surveying engineering introduces new monitoring procedures. Hence, structure deformations can be measured via reflectorless total station instruments; in addition to that, ground-based laser scanners may be applicable. The question that arises is whether the accuracy achieved by those instruments meets the expectations of such a task.

This paper attempts to evaluate the monitoring-performance of a reflectorless total station and that of a ground-based laser scanner through a plane-fitting case study. For this purpose, the defining parameters of a plane are determined through a least squares estimation, by using 3-Dimensional coordinates that derive by the application of the intersection technique. This plane serves as a standard against which the monitoring-performance of the aforementioned instruments is evaluated. Hence, these parameters are statistically compared to those that derive by the new monitoring techniques.

1. Introduction

Technical structures are subject to natural causes and to human interaction that may lead to collapse or structural failure. On the latter occasion the development of an appropriate methodology for the distant structure monitoring is crucial for safety reasons.

In order for such occasions to be confronted, engineers are appropriately equipped with instruments capable to cope with the special conditions arising. More specifically, the use of laser technology in surveying instruments' industry led to the development of reflectorless total stations and ground based laser scanners. In both instrument categories the use of special targets is not required. Hence, the need for distant monitoring in hazardous or not accessible environments is fulfilled. The problem arising is how accurately engineers can define the position of points or the mathematical equation of a specific surface. Hence, what needs to be certified is whether these instruments meet the high accuracy requirements arising on deformation monitoring occasions, not only examining deformation on the spot but also through changes of the surface equation parameters.

This paper attempts to investigate this matter through a plane fitting case study comparing the procedure followed by using the aforementioned instruments with that followed by using an accurate conventional instrument.

The second section of the paper describes a network created for the needs of the study case. The measurement procedures followed are dealt with in the third section. The derived results and the statistical tests are presented in the fourth section, and finally the conclusions and suggestions resulted are given in section five.

2. Network description

In order to examine the instruments' capabilities and the adopted methodology, a network was created in a laboratorial room in the School of Rural and Surveying Engineers of NTUA building which serves as a metrological laboratory.

The room is equipped with permanent pillars of forced centring, three of which were used for the purposes of the present paper. The pillar coordinates have been accurately calculated using invar tapes and therefore they were considered to be "known"(errorless). (fig.2.1).

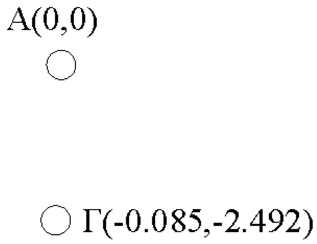

Fig. 2.1 Laboratorial pillars

Apparently, a coordinate system centered in point A is formed, while the Y-axis is the direction AB.

Twenty-one points were attached on the ceiling of the room. From the coordinates of these points, the components of the surface in which they belong could derive. The points were attached using pin-shaped targets in such a way so as to roughly form a grid covering a large portion of the surface of the ceiling.

Thus, a network of twenty-four points was created. Measurements were carried out from the three pillars to the twenty-one points that belong to the surface.

3. Methodology

For the plane determination a conventional surveying instrument of high accuracy (Leica TC1800) was primarily used, along with a reflectorless total station instrument (Leica TCR303) and a ground based laser scanner (CYRAX). The methodology followed on each occasion is analyzed in the following sections.

3.1 TC 1800 Total Station Instrument

The TC1800 Leica instrument was used as a reference instrument for the measurements. The aforementioned instrument is of a $\pm 3^{cc}$ accuracy in angles (DIN 18723) and of a ±(2mm+2ppm) accuracy in distances (Leica TC1800 manual).

Given the demanded high accuracy, no distances were measured in order to assign horizontal coordinates (X,Y) to the twenty one points. Moreover, this would require the existence of a prism, which was not possible. Instead, only horizontal angles were measured and the scale of the network was given thanks to the known coordinates of the pillars. The instrument was set in all three pillars targeting all the unknown points. The temporary coordinates of the latter derived by intersection. Due to measurement redundancy the Least Squares Method was applied in order to calculate the best values of the coordinates. For that purpose, a program created in Qbasic programming language by the General Geodesy Laboratory was used (Balodimou, 1998). The accuracy achieved was ±3mm horizontally and ±1mm vertically.

As far as the third dimension H (height) of each point is concerned, inverse leveling was carried out using the Leica NA2000 digital level. The height of the points could alternatively derive by measuring vertical angles along with horizontal ones, but leveling was preferred for higher accuracy.

The components of the best fitting plane derived through a least squares estimation that used as input data the 3D coordinates of the twenty-one points. This plane served as a standard plane to which the planes derived by other methods were compared. The components of this plane are shown in Table 4.1 [TC1800(1)].

3.2 TCR 303 Total Station Instrument

The TCR 303 Leica instrument is a reflectorless total station of a $\pm 9^{cc}$ accuracy in angles (DIN 18723) and of a ±(3mm+2ppm) accuracy in distances. The maximum range of the distance measurement in reflectorless mode is 100m (Leica TCR303 manual).

The procedure followed is similar to the one that has been described for the Leica TC 1800 instrument, with the addition that vertical angles and distances were measured**.** It should be mentioned that special care was taken in point targeting so that the instrument's laser beam "centered" the targets. This ensured the correct distance measurements to the ceiling targets. The final 3D coordinates of the 21 points derived by processing the aforementioned measurements [Table 4.1, TCR303(2)]. The accuracy achieved was ±5mm horizontally and vertically.

Random points on the ceiling surface were also targeted using the TCR 303 positioned only on pillar A. The coordinates of these points derived through a similar process as described above. The components of the plane to which they belong were also calculated [Table 4.1, TCR303(3)].

3.3 CYRAX Ground based scanner

In order for the plane to be determined a ground based laser scanner was also used. The innovation of ground based laser scanners consists in the use of laser technology for measuring distances to a large amount of inaccessible points, of the order of a million. The measured distances are combined with angle and inclination measurements (via special sensors) to provide three-dimensional coordinates (Gordon at al., 2000)

The laser scanner used for the present application was the CYRAX instrument . The laser beam of the aforementioned instrument is of a span of 40^{o} in the horizontal plane and 40^{o} in the vertical plane. The distance measurement accuracy is of the order of ±6mm at distances up to 50m, while it decreases in greater distances that reach 150m, which is the maximum range of the instrument (CYRAX manual).

For the scanning of the ceiling surface to be completed, CYRAX was placed at three random locations in the laboratorial room. The instrument's orientation in the local coordinate system was accomplished via special reflective targets placed on the laboratorial pillars. The combination of the different scannings in a uniform system, along with the orientation of the measurements in the local system was accomplished via the use of the software accompanying the instrument.

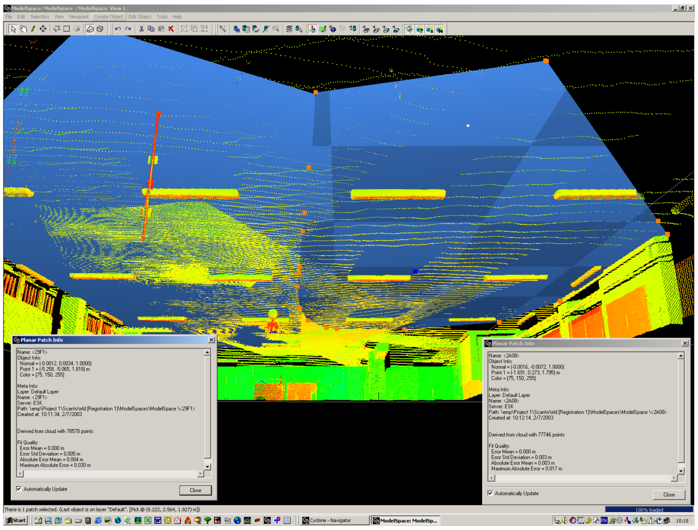

Figure 3.3.1 Ceiling scanning

4. Results and comparisons

The plane equation used was the following:

$$Ax + By + Gz + D = 0 \text{ or} \tag{4.1}$$

$$\frac{A}{G}x + \frac{B}{G}y + z\frac{D}{G} = 0 \Rightarrow z = ax + by + c \tag{4.2}$$

The best values of the components a,b,c along with their a posteriori standard errors and the variance of the unit weight, derived after the adjustment for each case, were as shown in table 4.1.

	a	b	c	σ_a	σ_b	σ_c	$\hat{\sigma}_o^2$
TC1800(1)	$9.338\cdot10^{-4}$	$6.685\cdot10^{-5}$	1.8326	$4.78\cdot10^{-4}$	$7.54\cdot10^{-4}$	$3.40\cdot10^{-3}$	$1.793\cdot10^{-4}$
TCR303 (2)	$9.341\cdot10^{-4}$	$-2.547\cdot10^{-5}$	1.8295	$4.72\cdot10^{-4}$	$7.45\cdot10^{-4}$	$3.36\cdot10^{-3}$	$1.755\cdot10^{-4}$
TCR303 random (3)	$6.79\cdot10^{-4}$	$4.11\cdot10^{-4}$	1.8264	$3.52\cdot10^{-4}$	$5.59\cdot10^{-4}$	$2.29\cdot10^{-3}$	$1.782\cdot10^{-4}$
CYRAX(4)	$8.00\cdot10^{-4}$	$-3.00\cdot10^{-4}$	1.8170	$7.87\cdot10^{-5}$	$1.76\cdot10^{-4}$	$4.46\cdot10^{-4}$	$7.569\cdot10^{-5}$

Table 4.1 Plane components for each case

The primary conclusion made after examining table 4.1 is that when discrete points are targeted (cases 1 and 2) the components of each plane and their standard deviations are almost equal. On the contrast, when random points are targeted (cases 3 and 4) the components of the plane differ from those of the standard (case 1). This is due to the fact that in these cases the number of the points is rather, large covering a bigger portion of the ceiling. Thus, random topical irregularities of the surface are taken into account, influencing the result.

A statistical test was carried out in order to evaluate the derived results, that is to estimate whether the calculated planes coincide, based on two assumptions:

1) The plane calculated using the TC1800 would be considered the standard to which the rest would be compared. This decision was made because the procedure followed was the traditional one and the point coordinates calculated using the TC1800 were the most accurate.
2) In order for the plane components to be statistically tested, the Student distribution should be used for case 1 and 2. This is due to the degrees of freedom that were 18 < 30. On the contrast, the normal distribution should be used for cases 3 and 4. For cases 1 and 2 the total degrees of freedom amount to 36 > 30, hence, the distribution used for the statistical tests was the normal one.

The successful statistical testing concerns the hypothesis H_0 according to which the two planes coincide for a specific confidence level. On the contrast, if the two planes statistically differ, the hypothesis H_α is fulfilled (Balodimou, 2000).

The statistical tests were carried out for a level of confidence of 95% based on the formula

$$-z_j \leq \frac{\Delta i}{\sigma_{\Delta i}} \leq z_j \qquad (4.3)$$

where Ti is the difference of each component from its respective one of the standard plane, σ_{Ti} is the standard deviation of Ti and z is the value of the standardized random variable for a confidence level of j. If j=95% then $z_{95} = 1.960$.

Based on formula 4.3, the inequality 4.4 should be valid in order for the test to be successful.

$$|\Delta_i| \leq z_j \cdot \sigma_{\Delta i} \qquad (4.4)$$

Each plane was primarily compared to the standard one (case 1). The absolute value of the difference between each factor should be smaller than a certain limit, according to the confidence level. The test for the planes 2 and 3 was successful, implying that their components a,b,c do not statistically differ for a confidence level of 95%. The control for case 4 was not successful. The original accuracy of the coordinates that derived through the scanner is ±6 mm horizontally according to the manufacturer's specifications, while the accuracy achieved by the TC1800 is about ±3 mm. Furthermore the plane derived by the scanner is actually a mean plane of the ceiling, since it has a width of some millimeters, which derived including any regional irregularities of the ceiling. Hence, the failure of the control must be due to the fact that the plane defined from discrete points was compared to one produced by a point cloud.

Additionally, another statistical test is possible via the ratio $\frac{\hat{\sigma}_{oj}^2}{\hat{\sigma}_{oi}^2}$, where $\hat{\sigma}_{oi}^2$ is the a posteriori variance of the unit weight, as it was calculated for the standard plane, and $\hat{\sigma}_{oj}^2$ is the a posteriori variance of the unit weight for each plane to be examined (Dermanis, 1996).

The test is carried out using the F distribution for a confidence level of 95% based on formula 4.5

$$\frac{\hat{\sigma}_{oj}^2}{\hat{\sigma}_{oi}^2} \leq F_{r_1, r_2, p} \qquad (4.5)$$

where r_1 is the degree of freedom for each of the examined planes, r_2 is the degree of freedom for the standard plane and p is the confidence interval (Balodimou, 2001).

The statistical test was valid for the planes of cases 2 and 3 for 95% confidence level. However, the test failed on the occasion of the plane of case 4. The same mathematical model (formula 3.2) was used for all cases.

It should be noted that if the statistical test using the F distribution is valid, then the test involving the plane components is also valid.

5. Conclusion

Considering the differences between the conventional instrument and the reflectorless total station instrument, the following remarks could be mentioned:

For the plane determination from the 2D coordinates of the targeted points, a predetermined network of points is essential on the occasion of conventional instruments, for the completion of the intersection method. The third dimension can be defined through leveling. In addition to that, the existence of special geodetic targets is also of high importance. However, due to the hardly accessible, and sometimes of hazardous nature, measurement environments, the attachment of any kind of target to the surfaces to be monitored is impossible. On the contrary, reflectorless instruments do not require the existence of geodetic targets, since they can directly acquire distance measurements and hence, provide 3D coordinates. In spite of this advantage, there is a range limitation of the order of 100m and the accuracy achieved depends on the nature of the targeted material and also on the incidence angle. Even though there are differences in the procedures followed, the derived, via the two kinds of instruments, planes were statistically identical. This indicates that reflectorless total station instruments constitute a powerful tool in monitoring structural deformation if the operation conditions are fulfilled (the maximum distance between the instrument and the structure must be less than 100 m and the expected magnitude of deformation more than 4 mm). Alternatively, reflectorless total station instruments with the ability to scan an area using a user-defined step have been developed, although not used for the purposes of this article.

As far as the ground based laser scanners are concerned, it could be stated that the derived surface is a result of the combination of multiple scans acquired from random positions. The user intervenes in the procedure of the surface derivation through the software accompanying the laser scanner, by setting conditions regarding the quantity of the points defining the aforementioned surface, such as the amount of scans taken into consideration and the tolerance of the points belonging to the surface. In addition, the surface derived by laser scanners results from a point cloud that consists of thousands of points. Hence, the majority of the surface irregularities is taken into consideration in the surface derivation, which probably is the reason for the lack of coincidence between the standard plane and the derived from the laser scanning one. The difference between the two planes does not prove the incapability of the laser scanners in monitoring structure deformations.

In conclusion of this article, it could be stated that ground based laser scanners along with reflectorless total station instruments constitute new monitoring equipment for the successful determination of structure deformation. Moreover, ground based laser scanners could produce satisfactory results in periodical structure monitoring, since the quality and the quantity of the spatial information would be the same. It is worthwhile to investigate the laser scanners' ability in determining deformations on more complex surfaces.

Acknowledgements

We would like to express our gratitude to I.G.DGroup Hellas for lending us CYRAX laser scanner and its software.

References

A.M.Agatza-Balodimou, (2000). Theory of errors and adjustments I.NTUA Edition, Athens.

A.M.Agatza-Balodimou,(2001). Theory of errors and adjustments II.NTUA Edition, Athens

A.M.Agatza-Balodimou,(1998). ADJ3D – Program in QBasic for 3D network adjustment using Least Square Estimation. NTUA Athens

A. Dermanis (1996). Observation adjustments and estimation theory. Ziti Edition, Thessaloniki

Stuart Gordon, Derek Lichti and Mike Stewart (2001). Application of a high - resolution, ground-based laser scanner for deformation measurements. Orange, California USA

Joseph H. Kindle (1950). Analytic Geometry. McGraw-Hill Company

Leica TC 1800 Manual

Leica TCR 303 Manual

CYRAX Manual