The Use of Geodetic Methodology in Precast Concrete Building Assembling

George D. GEORGOPOULOS and Elisavet C. TELIONI, Greece

Key words: precast assembling, divergences of precast elements, geodetic methodology, construction monitoring.

SUMMARY

In concrete construction, discrepancies occur between the nominal values of the building's geometric features, and those finally resulting after the construction. Especially, in precast construction if the magnitude of discrepancies (named *divergences*) exceeds an upper limit, specified by the precast construction rules (named *tolerances*), deterioration of the building's bearing ability is possible.

Divergences in precast construction may occur during the fabrication, storage and transportation of the concrete elements (slabs, beams, columns and foundation elements) in place. This kind of divergences mainly concern the elements' dimensions and fabrication quality. Therefore, they can be minimized if special precautions are taken. Divergences, also occur during the consecutive stages of the precast assembling, due to incorrect positioning, declinations from vertical position and displacements of the precast elements. It is this kind of divergences that might prove responsible for the deterioration of the building's bearing ability.

In order to ensure the correct positioning of the various elements throughout the precast assembling, a geodetic control network is established in the vicinity of the construction. The special features of optimization and design of the network are analyzed, and the whole procedure during the various successive stages of the assembling is described. Following, after the building's erection, the methodology for the estimation of the finally achieved accuracy, is given.

A case study is presented. This case study presents the application of the above, briefly described geodetic methodology throughout the precast assembling of a three floor building. The determination of the final divergence vectors, the test of their statistical significance and the comparison of their magnitude against the given tolerances is also presented.

Finally, the conclusions withdrawn and the suggestions made are given.

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1. INTRODUCTION

In concrete construction, and especially in precast concrete construction, discrepancies inevitably occur between the nominal values of the building's geometric features, given in the construction plans, and those finally realized. Apart from the aesthetic point of view, if the magnitude of discrepancies (otherwise called *divergences*) exceeds an upper limit, specified by the precast construction rules as *tolerance*, deterioration of the building's bearing ability is possible.

In precast concrete constructions, the effect of the divergences in the construction's behavior is of prominent importance, since it is a combination of divergences concerning the fabrication quality and the precast elements' dimensions and divergences occurring during the consecutive stages of the building's assembling (Georgopoulos – Telioni, 2003).

In this paper the use of geodetic methodology in precast construction is presented, in order to:
- reduce the magnitude of divergences, during the assembling, and
- reliably estimate and test the statistical significance of the final divergence vectors in the positioning of the precast elements, as well as those of the geometric features of the construction, after the building's erection.

Through this methodology it is also possible to determine deformations of the construction due to various causes such as earthquakes, temperature variations, differential subsidences of the foundations, fire etc.

2. MONITORING THE GEOMETRY OF A PRECAST CONSTRUCTION

2.1 The Geodetic Control Network

In order to ensure the correct positioning of the various elements throughout the precast assembling, a geodetic control network is established in the vicinity of the construction, before the beginning of the works.

Since the network is going to be used throughout the consecutive stages of the assembling, as well as for the determination of the horizontal divergence or displacement vectors after the completion of the construction, *the optimum reference system is a local geodetic coordinate system*. The network's geodetic datum is defined by the minimum constraints, i.e. one point and one azimuth fixed, making the assumption that the coordinate system is centered to the fixed point (*Zero Order Design*). The fixed point should be located to the most stable area of the surroundings of the construction, and its stability must be checked at regular intervals.

The answer to the *First Order Design* problem (number and position of the network's points) is imposed by the size and the geometric characteristics of the building, than the optimum location of the network's points. Given that the network is going to be used throughout the various stages of the construction, the points' monumentation should be permanent.

The selection of the instrumentation to be used for the measurement of the network's elements, depends on the predefined accuracy of the points' coordinates (usually of some mm), according to which the accuracy of the observations is determined (*Second Order Design*). Moreover, it is also important to determine the *sensitivity* of the network, i.e. determine the minimum horizontal divergence vector $(min\,\delta r)$ that can be reliably estimated by the network. The sensitivity of such a network, concerning the horizontal divergence vector between i, j points, is determined through the equation:

$$min\,\delta r = z_{0.99} \cdot \sigma_{\delta r\, max}$$

where:

δr : the horizontal divergence vector, and

$\sigma_{\delta r\, max}$: the major semi-axis of the error ellipse of the divergence vector, determined through the a priori covariance sub-matrix $V_{\delta r_i}$.(Krakiwsky, 1991, Kuang, 1991)

The adjustment of observations leads to the estimation of the points' coordinates and their standard errors. The global test on the a posteriori $\hat{\sigma}_0$ and Baarda's data snooping on the observations are also applied in order to check the accuracy and reliability of the network. (Krakiwsky, 1991).

The monitoring of the geometry of a precast construction consists of the following consecutive stages: (Tsoukantas, 2002)

- Setting out the foundation grid,
- Monitoring the in place positioning of the different precast elements,
- Estimation of the final divergence vectors after the building's erection, and
- Monitoring the kinematic behavior of the construction (if necessary).

2.2 Setting Out the Foundation Grid of the Construction

The setting out of the foundation grid consists of the field and office works, as a whole, in order to determine accurately the position of the centers of the precast concrete foundation elements (cones). The coordinates of the centers of the cones are determined in the office from the construction plans, in the reference system of the network, and the corresponding polar coordinates from the network points are calculated. The cones centers' setting out is carried using total stations of high precision. Experience shows that an accuracy of $\pm 1cm$ (or even better) can be achieved if special care in the instrument centering is given.

2.3 Monitoring of the Precast Elements' Positioning in Place

The monitoring of the positioning in place concerns primarily the control of the vertical positioning of the precast columns during the erection. Two control points are established, on the upper and lower part of the symmetry axis of at least one side of each column. Their position is determined through angular and length observations from arbitrarily chosen points, which need not belong to the network's reference frame. The observations are carried out using total stations of high precision, with the capability of length measurements without prisms (reflector less). The corresponding polar coordinates of the control points are, consecutively, determined in field from the instrument's software. Thus, the column's vertical position is directly controlled in site through the comparison of the control points' coordinates. It must be pointed out that it would be very useful if the marking of the control points is done during the column's fabrication in the factory.

The control of the building's dimensions is also possible at this stage. This monitoring consists of checking distances between columns as well as distances between critical elements of the precast construction such as distances between junction pegs etc. (Tsoukantas, 2002)

2.4 Estimation of the Elements' Final Divergences

After the building's erection the discrepancies between the "as built" and the "as designed" situation can be determined, through the estimation of the elements' final divergences and the comparison of their magnitude against the given tolerances. For this purpose, control points are established on the construction elements. The control points are usually established on the precast columns: a pair of points on each column's symmetry axis of at least one side, on the upper and lower part of it, respectively. These points, if possible, are the same with those used during the building's assembling (§ 2.3). Thus, it is possible to determine various kinds of divergences, such as declinations from vertical position, dimension differences from the construction plans.

The control points are hence incorporated in the geodetic control network. The network's elements are re-observed, and the final divergences of interest are derived through the comparison of the estimates of the control points' coordinates after the adjustment of the observations. Finally, the statistically significant divergences are compared against the preset tolerances. (Georgopoulos, 2000)

2.5 Monitoring the Kinematic Behavior of the Construction

Displacements of the precast elements may also occur due to accidental causes (earthquake tremors, differential subsidence of the foundations etc), with a serious effect on the bearing ability of the construction.

The magnitude of the above mentioned displacements can be estimated through a re-observation of the geodetic control network elements. The estimated coordinates of the network's control points are then compared to the former ones, and the corresponding vectors of displacement are estimated and tested for their statistical significance. From the displacement vectors the deformation parameters of the precast elements are also estimated. Moreover, by estimating the displacement vectors, in successive, especially selected, time intervals, the kinematic behavior of the construction is monitored.

3. A CASE STUDY

The presented above geodetic methodology was applied throughout the assembling of a precast construction (a newspapers publishing house). The construction consists of two buildings: a one-floor building where the printing press machines are installed, and the three-floor building of the newspaper headquarters.

A geodetic control network was established in the vicinity of the construction, just after the excavation works. The network consisted of 10 points (K1, …, K10). The Total Station TC1600 WILD, having an accuracy of 0.3mgon in angle measurements and $\pm(3mm \pm 2ppm)$ in length measurements was used for the observations. 15 distances and 20 angles were observed as a whole. The adjustment of the observations was performed with the minimum constraints: point K10 together with the azimuth of the side K10-K9 were kept fixed. From the adjustment of the observations, the coordinates of the network's points and their standard errors (ranging from $\pm 2mm$ up to $\pm 6mm$) were determined in a local reference system. The null hypothesis was accepted from the global test of the network ($\hat{\sigma}_0 = \pm 1.10$) while no observation was rejected when Baarda's data snooping was applied.

3.1 The Precast Assembling Using the Geodetic Methodology

The coordinates of the centers of the 54 foundation cones were determined from the construction plans, in the reference system of the network. By applying the law of error propagation it was realized that the coordinates of all points had an accuracy of the range of $\pm 1cm$. The centers' setting out was carried out using the total station TC1600, Wild. The differences between the nominal distances of the foundation cones centers (as given from the construction plans) and those realized in site were of the range of $\pm 1cm$.

The control of the vertical positioning of the precast columns was carried out with the TCR303, Wild that has the capability of distance measurements without prism. A pair of control points was marked on the symmetry axis of at least one side of each column, and the verticality of the column was checked in two directions, perpendicular to each other. At the same stage, the distances between opposite columns were also checked. (Fig.1)

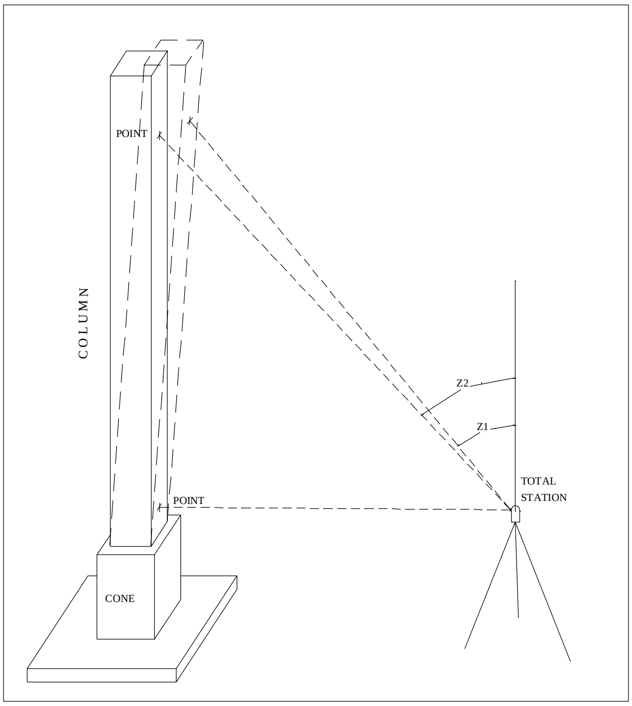

Fig. 1: Monitoring a column’s declination

3.2 Estimation of the Final Total Divergences after the Erection

In order to define the accuracy achieved, the final divergences were determined and compared:

- against the permitted tolerances, and
- against those determined in a two-floor precast construction, having approximately the same dimensions with the one under consideration, where the geodetic methodology had not been used during the assembling. (Georgopoulos – Telioni, 2003)

It was decided to determine the divergence vectors of the three-floor building where, because of the columns’ height, the most serious divergences were expected (Fig 2).

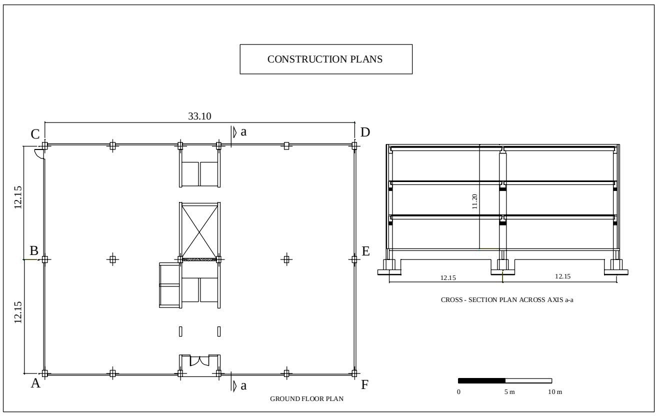

Figure 2: Construction plans of the three – floor precast building

Unfortunately, all the points of the former geodetic control network were destroyed; therefore a new geodetic control network was established (Fig.3). The network consists of *14 reference and 16 control points*: 6 of the reference points are established in the surroundings of the construction (K_1, …, K_6), 4 more are established on the building's 2nd floor (K_7, …, K_{10}) and the remaining 4 (K_{11}, …, K_{14}) on the building's roof. The control points are established on six of the building's perimeter columns. Four of the columns are situated at the building's corners; for that reason, two control points are established at the lower part of each column's adjacent, outer sides (C_{11}, C_{12}, C_{31}, C_{32}, C_{41}, C_{42}, C_{61}, C_{62}). Six more control points are established on the upper part of the corresponding columns' interior side (C_{13}, C_{21}, C_{33}, C_{43}, C_{51}, C_{63}). These points are those marked and used for the monitoring of the columns' vertical positioning during the assembling stage.

The observations of the network's elements were carried out using the total station TC1600. WILD.62 distances and 79 angles formed the observation scheme. The adjustment of the observations was performed with the minimum constraints: point K_4 together with the azimuth of the side K_4 - K_1 were kept fixed ($X_{K4} = Y_{K4} = +1000.000$m, $a_{K4\text{-}K1} = 50.8192^g$). From the adjustment of the observations, the estimates of the network's parameters and their standard errors were determined, in a local reference system. (Table 1.) The null hypothesis was accepted from the global test of the network ($\hat{\sigma}_0 = \pm 1.02$) while no observation was rejected when Baarda's data snooping was applied.

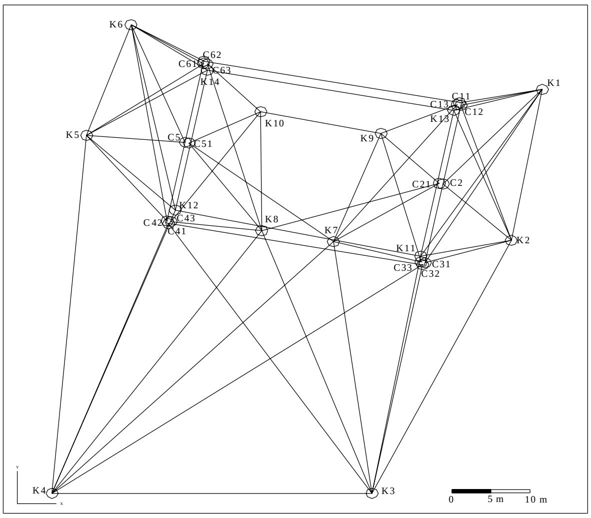

Fig. 3: The geodetic control network

	REFERENCE POINTS					CONTROL POINTS			
	X (m)	σ_X (mm)	Y (m)	σ_Y (mm)		X (m)	σ_X (mm)	Y (m)	σ_Y (mm)
K_1	1062.723	±1.6	61.129	±1.5	C_{11}	1052.145	±5.0	1059.149	±5.0
K_2	1058.747	±1.4	1038.288	±1.3	C_{12}	1052.327	±1.7	1058.754	±1.5
K_3	1040.951	±1.3	1000.003	±0.9	C_{13}	1051.829	±3.1	1058.851	±3.0
K_4	1000.000	±0.0	1000.000	0.0	C_2	1050.033	±1.5	1046.836	±1.4
K_5	1004.426	±1.2	1054.175	±1.5	C_{21}	1049.547	±2.2	1046.942	±2.3
K_6	1010.100	±1.6	1070.951	±1.9	C_{31}	1047.731	±2.2	1034.903	±1.5
K_7	1036.009	±1.6	1038.092	±1.9	C_{32}	1047.417	±4.1	1034.608	±3.1
K_8	1026.828	±1.6	1039.746	±1.8	C_{33}	1047.236	±2.1	1035.004	±2.3
K_9	1042.100	±2.2	1054.484	±2.4	C_{41}	1014.918	±2.7	1040.835	±4.1
K_{10}	1026.720	±2.2	1057.769	±2.2	C_{42}	1014.741	±1.7	1041.225	±2.5
K_{11}	1047.165	±1.3	1035.875	±1.3	C_{43}	1015.216	±2.2	1041.136	±1.7
K_{12}	1015.781	±1.1	1042.898	±1.4	C_5	1017.039	±1.7	1053.168	±1.6
K_{13}	1051.404	±1.3	1058.004	±1.4	C_{51}	1017.530	±2.2	1053.055	±2.0
K_{14}	1019.871	±1.7	1064.050	±1.6	C_{61}	1019.354	±1.9	1065.083	±1.8
					C_{62}	1019.435	±5.0	1065.425	±5.0
					C_{63}	1019.840	±2.8	1065.017	±3.1

Table 1: Coordinates of the Geodetic Control Network's Points

The following divergences were estimated, using the estimated coordinates of the control points:

3.2.1 <u>Departures of the building's "as built" dimensions against the "as designed" ones</u>.

All of the building's dimensions are given in the construction plans, from columns' axis to axis. According these plans, the building's dimensions are 33.10m(side AF) by 24.30m (side AC, respectively). The corresponding dimensions after the building's erection, using the estimated coordinates of the control points are depicted in Table 2.

<table>
<tr><th colspan="2">SIDE</th><th colspan="2">AS DESIGNED</th><th colspan="2">AS BUILT</th></tr>
<tr><td colspan="2">AF</td><td colspan="2">33.10m</td><td colspan="2">33.09m</td></tr>
<tr><td colspan="2">CD</td><td colspan="2">33.10m</td><td colspan="2">33.08m</td></tr>
<tr><td rowspan="2">AC</td><td>AB</td><td rowspan="2">24.30m</td><td>12.15m</td><td rowspan="2">24.30m</td><td>12.16m</td></tr>
<tr><td>BC</td><td>12.15m</td><td>12.14m</td></tr>
<tr><td rowspan="2">DE</td><td>EF</td><td rowspan="2">24.30m</td><td>12.15m</td><td rowspan="2">24.29m</td><td>12.15m</td></tr>
<tr><td>DE</td><td>12.15m</td><td>12.14m</td></tr>
</table>

Table 2: "As built" dimensions of the building's sides compared to the "as designed" ones

From the above table it can be seen that the maximum departure of the dimensions of the construction is 0.02m. All departures are statistically significant, since the standard deviation of the estimated dimensions is of the range of ± 0.003m.

The corresponding departures of the two-floor precast construction, where geodetic methodology has not been used during the assembling, are significantly greater, ranging from 0.025m up to 0.057m.

It must be pointed out that, according to the Greek rules for precast construction, the tolerance A in dimensions' departures is $A \leq 30mm$ for the total dimension of a side of the building and $A \leq 20mm$ for the departure between consecutive columns. (Tsoukantas,1988, Technical Chamber of Greece,1991)

Therefore the estimated departures in the precast building, where geodetic methodology was used during the assembling, are less than the given tolerances.

3.2.2 <u>Departures of columns from vertical position</u>

Making the assumption that the columns were fabricated without error, i.e. having dimensions 0.50m by 0.70m, then the horizontal distance between point C_i of the lower part of the column and point C_j at the upper part of it, should be 0.50m, should the column be in vertical position. Otherwise, this distance would be either smaller or greater than 0.50m.

From the estimated standard errors of the control points' coordinates (Table 1.) by applying the law of propagation of errors, it was estimated that the standard deviation of the distance between the two control points of each column is of the range of $\sigma_l = \pm 0.003m$. Therefore, every departure $d_l \rangle \sigma_l \cdot z_{0.95} = 0.003 \cdot 1.96 = 0.006m$ of the control points' distance from the correct dimension (0.50m), is statistically significant.

The distances between the control points of each column under consideration, as well as their departures from the correct dimension are depicted in Table 3. The statistically significant departures are given with bold characters. Since the vertical distance between the upper and lower control point of each column is, approximately, 10m, the inclination of the columns having statistically significant departures from the vertical position are also given.

COLUMN	POINTS	DISTANCE	DEPARTURE	INCLINATION
A	C42-C43	0.483m	**-0.017m**	**0.002rad**
B	C5-C51	0.504m	0.004m	0
C	C61-C63	0.490m	**-0.010m**	**0.001rad**
D	C12-C13	0.507m	**0.007m**	**0.001rad**
E	C2-C21	0.497m	-0.003m	0
F	C31-C33	0.505m	0.005m	0

Table 3: Departure of columns from vertical position

The departures of columns from vertical position in the case of the two floor precast construction, where geodetic methodology has not been used during the assembling, range from 0.022m (0.003rad) up to 0.052m (0.008rad).

The corresponding tolerance A, given by the Greek rules for precast construction is $A \leq 0.003rad$. (Tsoukantas,1988, Technical Chamber of Greece,1991)

Therefore, the estimated inclinations of the columns of the precast building, where geodetic methodology was used during the assembling, are less than the given tolerances.

4. CONCLUSIONS - SUGGESTIONS

From the methodology proposed to be used throughout the precast assembling, as applied in the above case study, as well as from the estimated final divergences, the following conclusions-suggestions are withdrawn:

- Geodetic methodology, used through out the precast assembling, is a reliable tool for the minimization of divergences of the precast elements. According the experience obtained through its application in the above case study, an overall accuracy of $\pm 1cm$ in the positioning of the various precast elements can be easily achieved.
- The accuracy of $\pm 1cm$ in the precast element positioning is absolutely satisfactory since the divergences in both the dimensions of the construction as well as the departure of the precast columns from vertical position were, in the above case study, of the range of $\pm 1cm$ for the dimensions and of the range of 0.002rad for the columns' inclination. Both of the above divergences are smaller than the *tolerances*, given by the Greek rules for precast construction.

- The reference points of the network should be established before the beginning of the construction works, in safe and stable locations and their monumentation should be permanent.
- It would be very useful if the marking of the control points at the selected positions is done during the precast elements' fabrication in the industry.
- Since a large number of the control points of the network is inaccessible, the use of reflectorless total stations of appropriate accuracy, for the measurement of the network's elements, permits the measurement of all the sides between the reference and the control points of the network. Therefore the network's scale will be stronger and the quality of the results better.
- The geodetic control network established for the precast assembling can also be used for the monitoring of the construction's kinematic behavior, after its erection. This is especially important in areas where the seismic hazard is great. Therefore the stability of the reference points of the network should be ensured. For this purpose GPS measurements can be used where possible.

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BIOGRAPHICAL NOTES

Dr George D. Georgopoulos, Lecturer of the School of Surveying & Rural Engineering, N.T.U.A.
Dr Elisavet C. Telioni, Lecturer of the School of Surveying & Rural Engineering, N.T.U.A.

CONTACTS

George D. Georgopoulos
School of Rural & Surveying Engineering, Department of Topography,
Laboratory of General Geodesy, National Technical University of Athens, Greece.
9, Heroon Polytechniou str., 157 80, Zografos
Athens
GREECE
Tel. + 30 210 772 2729
Fax + 30 210 772 2728
Email: gegeorgo@central.ntua.gr

Elisavet C. Telioni
School of Rural & Surveying Engineering, Department of Topography,
Laboratory of General Geodesy, National Technical University of Athens, Greece.
9, Heroon Polytechniou str., 157 80, Zografos
Athens
GREECE
Tel. + 30 210 772 2726
Fax + 30 210 772 2728
Email: telioni@survey.ntua.gr