A Geodetic Deformation Survey to Monitor the Behavior of a Concrete Slab During Its Axial Compression Testing

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Key words: Deformation monitoring survey, deformation analysis, etc.

SUMMARY

A deformation survey exercise has been performed to monitor the behavior of a small engineering object i.e., a 455cm x 240cm x 120cm lightweight concrete slab. The survey was carried out in conjunction with the axial compression testing conducted upon the slab to determine its axial strength. The tests were done by applying a series of load beginning with 0kN and then steadily increased to 200kN, 258, 300 and 375 kN standard respectively.

A micro geodetic network consists of five reference stations has been established in the laboratory where the compression tests were conducted. A number of target points have been located on the concrete block and 2D triangulation measurements consist of direction and distance observations were read to each target. A total of five epochs of measurement data were gathered and adjusted using least squares estimation (lse) procedure. The measurement epoch was corresponding to the five different loads applied during the above test. The coordinates difference obtained from lse computation indicates that the displacement vector at some of the target points is to the magnitude of 10 to 17 mm.

This exercise demonstrates the capability of geodetic monitoring survey technique in providing 2D displacement vector information for a sample of concrete slab for civil engineering application.

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1. INTRODUCTION

Deformation survey for monitoring purposes has been used in many disciplines for various applications. Among typical examples is the applications of the deformation monitoring in geodesy to identify the crustal deformation or tectonic movements at global or regional scale. The deformation survey is also regularly conducted to monitor the behaviour of engineering structures such as dams, bridges, rail track and etc. These types of work is classifies as local scale as the network involves is relatively small in area.

The tasks in deformation monitoring survey require acquisition of observation data obtained from more than one campaign of field measurements. Type of instruments used in data acquiring is depending on the nature of works and also on logistical consideration. Normally, for a small network the use of theodolite and total station seems good enough in measuring the required directions or horizontal angles and distances. The subsequent task is to perform the least squares adjustment to determine the coordinates of all the reference as well as the object points in the network for each epoch of measurements. Further, in monitoring works the exercise is continues with the analysis of deformation emphasizing on two important aspects i.e., the solution to datum defect and selection of the right datum (Chen, 1983). These tasks are necessary in order to determine the correct displacements vector for all the monitoring points.

2. THE DEFORMATION MONITORING SURVEY

A deformation survey exercise has been conducted to monitor the behavior of a small engineering object, i.e., a concrete slab of 455cm x 240cm x 120cm in size (Figure 1). This work is a collaboration between the Surveying Engineering Research Group (SERG), Faculty of Geoinformation Science & Engineering and Laboratory of Material & Structural, Faculty of Civil Engineering UTM.

The deformation surveys were implemented by geodetic method from a small monitoring network established in the Laboratory where the compression tests take place. A total of 5 reference points were sited within an area of about 6m x 4m (Figure 2). A 2D triangulation measurements consists of direction and distances were observed using Sokkia Set3 Total Station.

The survey was carried out in conjunction with the axial compression testing conducted upon the slab to determine its axial strength. The axial compression testing was performed by the Material & Structure Research Group utilizing DARTEC testing machine (Figure 3). The test was implemented by applying a series of load beginning with 0kN and then steadily increased to 200, 258, 300 and 375 kN standard respectively.

Figure 1: Lightweight concrete slab

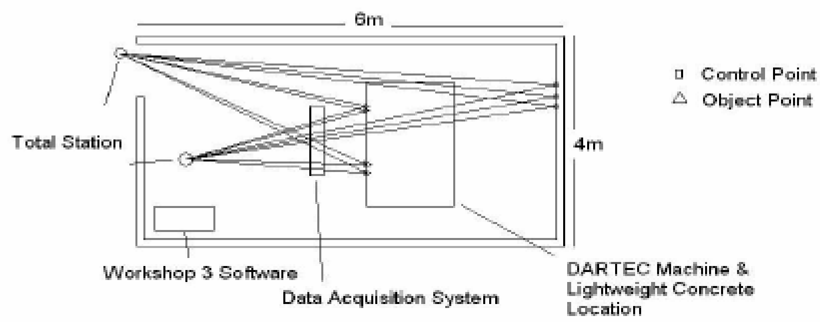

Figure 2: Monitoring network established in the laboratory

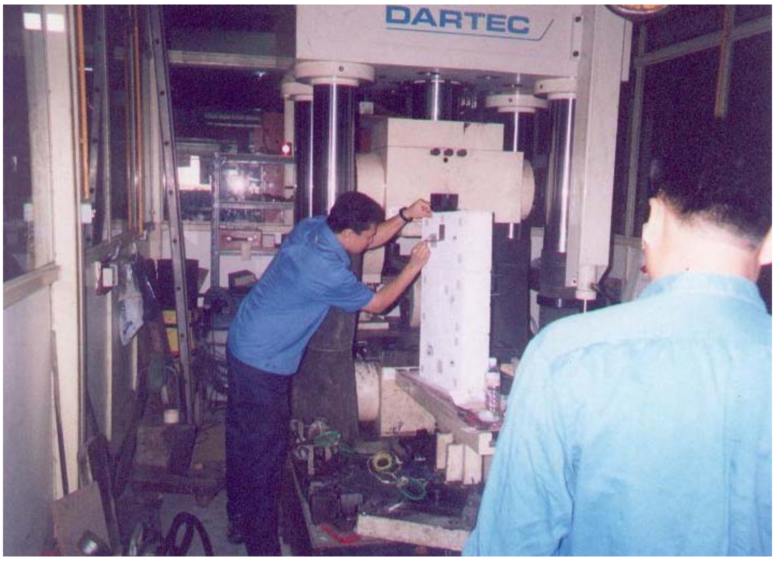

Figure 3: DARTEC Testing Machine

The monitoring survey consists a total of five epoch of measurements. Each epoch is identifies by the load utilized during the testing (i.e., 0kN, 200kN, 258kN, 300kN & 375kN). The survey data was collected by observation made to a total of seven object points located on one facade of the slab. All these points were marked with glued retro-tape and distributed as shown in Figure 4.

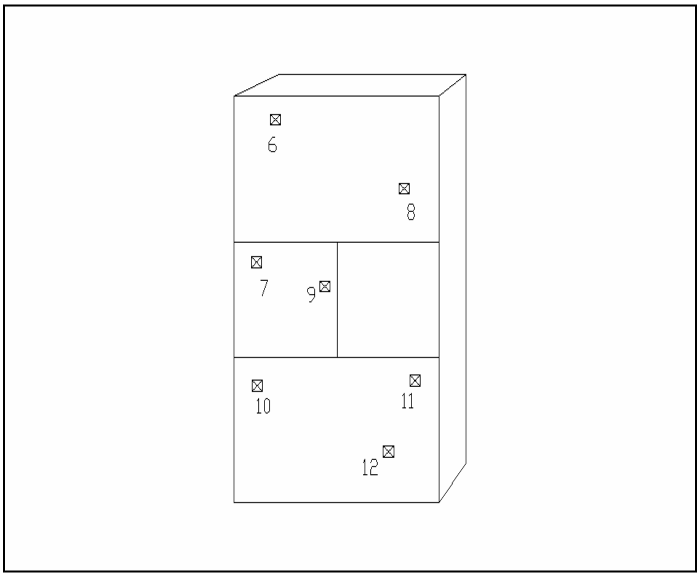

Figure 4: Position of retro-taped object points

3. THE MONITORING NETWORK LEAST SQUARES ADJUSTMENT

The analysis of deformation in geometrical aspect involves a two-step analysis. In the first step, coordinates for all points in the monitoring network are computed through a separate least squares adjustment for each measurement epoch. The second step of the analysis deals with deformation detection, which requires examining and comparing the adjustment results between any two epochs. This section is intended to discuss the aspects of least squares adjustment for monitoring network.

The measurements (eg., directions and distances) are to be relate to the parameter (i.e., coordinates) by mathematical equations and one such relationship is called functional model expressed as,

$$l = f(x) \qquad (1)$$

where, l is vector of the observation and x is vector of the coordinate to be estimate. Equation (1) generally is non-linear, hence needs to be linearized using Taylor's series. In least squares network adjustment equation (1) is further written as,

$$l + v = A x \qquad (2)$$

where, v is the vector of residuals and A is the design matrix. Solution to least squares estimate requires formation of a normal equation with a full rank which can be written as,

$$N\hat{x} + U = 0 \qquad (3)$$

and leads to the least squares solution for $\hat{x}$ as follows;

$$\hat{x} = -N^{-1}U = -(A^T PA)^{-1} A^T Pl \qquad (4)$$

where, N is referred to as normal equation matrix, P is the weight matrix for the observation.

Incorporated to the solution of least squares is the statistical testing procedures to verify the adjustment results worthiness. There are two types of statistical testing normally implemented which referred to as the global and local tests. The former employs chi-squares distribution and the latter is meant for blunder detection. If a particular test is not satisfied, it implies that either one or a combination of the following i.e., the mathematical model, the observational weight or computational procedures is or are to be reconsidered. For further details on least squares estimation the interested reader are referred to Cooper (1987), Harvey (1990) and Kuang (1996).

4. DEFORMATION DETECTION

The tasks of deformation detection is compound with two main issues, the problem of datum and the question relates to the reference points stability particularly between the two measurement epochs.

Generally, the deformation monitoring networks are mostly free networks suffering from datum defects incurred from rank deficiency due to configuration or datum defect problem. As a consequence, the datum defect has to be solved say by means of introducing constraints. Among the common choice of alleviating datum problem in the case of monitoring networks are the techniques of minimum constraints, minimum trace and partial minimum trace (Caspary, 1987).

In this research, the choice of datum selected for the initial least squares adjustment is by means of minimum constraint. Further, when comparing the results between any two-epochs, the method of S-transformation is advocates, in order to overcome the problem of datum-dependent displacements.

Next to be considered is the computational procedure with regards to the stable point analysis. One technique which is normally implemented is the congruency testing method as proposed in Chen (1983) and Caspary (1987). The objective of the congruency test is to detect whether or not the point group of a deformation network has remained stable. The test is based on F-statistics which requires the computation of an element $\hat{\sigma}_{oi}^2$, known as the pooled variance factor, computed for each combination epoch *i* which consists of for example epoch 1 and 2, 2 and 3 and so on.

Basically, the adopted procedure of congruency testing consists of the following (Caspary, 1987; Halim, 1995; Halim & Singh, 2001);

- Transformation of the displacement vector, *d* and its cofactor matrix, Q_d for both epochs into a common datum through *S*-transformation.
- Determination of stable datum points by congruency testing;

$$\omega = \frac{\Omega}{\left(h \bullet \hat{\sigma}_o^2\right)} = \frac{d_1'^T Q_{d_1}'^{+} d_1'}{\left(h \bullet \hat{\sigma}_0^2\right)} \sim F(\alpha, h, \partial f) \qquad (5)$$

where;

d_1' = the displacement vector of the datum points common in both epochs,

Q_{d_1}' = the cofactor matrix for the displacement vector d_1',

$\hat{\sigma}_o^2 = \frac{\left[\left(\hat{\sigma}_{o1}^2\right)\left(df_1\right) + \left(\hat{\sigma}_{o2}^2\right)\left(df_2\right)\right]}{df}$, the common or pooled variance factor.

$\hat{\sigma}_{o1}^2$, df_1 = *a posteriori variance* factor and the degree of freedom in epoch 1

$\hat{\sigma}_{o2}^2$, df_2 = *a posteriori variance* factor and the degree of freedom in epoch 2

$df = df_1 + df_2$, sum of degrees of freedom of epochs 1 and 2,

$Q_{d_2}'^{+} = \left(Q_{d_2}' + GG^T\right)^{-1} - G(G^T GG^T G)^{-1} G^T$, the pseudo inverse,

G is the inner constraint matrix constructed depending on the number of common datum points,

$h =$ rank $\left(Q'_{d_1}\right) = (2n - d)$ for a 2D network with n number of common datum points and d number of datum defects while α is significance level typically chosen as 0.05

- Localization of deformation through the single point test, S-transformation and congruency testing.
- Final testing on all common points by single point test.

$$T_j = \frac{\Omega}{2 \bullet \hat{\sigma}_o^2} = \frac{d_{1j}^{'T} Q_{d_{1j}}^{-1} d'_{1j}}{2 \bullet \hat{\sigma}_o^2} \sim F(\alpha, 2, df) \qquad (6)$$

where d'_{ij} and Q'_{dij} are the displacement vector and cofactor matrix of each datum point j.

5. RESULTS AND ANALYSIS

The tasks of least squares adjustment computation and subsequently the deformation detection have been solved using a computer package DEFORM99, developed by SERG, UTM. In DEFORM99, the initial least squares estimation employs the technique of minimum constraint as datum definition. Subsequently, the deformation detection algorithm is based on the combination of S-transformation with the congruency testing as discussed above, and the graphic presentation module is link with AutoCAD.

The least squares adjustment of the monitoring network which consists of 12 points, i.e., 5 reference points (Points No. 1 - 5) and 7 object points (Points No. 6 -12). Each measurement epoch consist of 22 azimuths (standard error assume as 2") and 15 horizontal distances (standard error of 2 mm). The least squares adjustment of each epoch is implemented by fixing the coordinates of x_1 and y_1. The significance value for the global and local test were chosen at 0.05. The outcome of the least square estimation is shown in Table 1.

Epoch No	Ep 1 - 0 kN	Ep 2 - 200 kN	Ep 3 - 258 kN	Ep 4 - 300 kN	Ep 5 - 375 kN
Datum definition	x_1, y_1	x_1, y_1	x_1, y_1	x_1, y_1	x_1, y_1
No. of datum defects	2	2	2	2	2
No. of observations	37	37	37	37	37
Degrees of freedom	15	15	15	15	15
No. of iteration	2	3	3	3	3
A posteriori variance	0.4357	0.4577	0.3842	0.5513	0.4747
Global test	0.238<1<1.044	0.250<1<0.096	0.210<1<0.920	0.301<1<1.321	0.259<1<1.137
Local test (Pope's Tau)	All passed	All passed	All passed	All passed	All passed

Table 1: Least squares adjustments summary

The computation for detection of deformation were subsequently follow based on two-epoch analysis with results of congruency testing shown in Table 2 and the displacement vector of all the monitoring points in Table3.

Two-epochs comparison	0kN & 200KN	0kN & 258kN	0kN & 300kN	0kN & 375kN
Pooled variance factor	0.4467	0.41	0.4935	0.4552
Test of the variance ratio	1.050 < 2.405	1.134 < 2.405	1.265 < 2.405	1.089 < 2.405
Global congruency test	0.702 < 2.265	0.685 < 2.265	0.384 < 2.265	0.120 < 2.265
Stable points detected	1, 2, 3 ,4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5
Moved points detected	6,7,8,9,10,11,12	6,7,8,9,10,11,12	6,7,8,9,10,11,12	6,7,8,9,10,11,12
Final selection of datum	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5

Table 2: Results of the congruency test

Control Points	Epoch comparison / Load combination			
	0kN & 200kN	0kN & 258kN	0kN & 300kN	0kN & 375kN
1	0.0014 m	0.0014 m	0.001 m	0.0005 m
2	0.0008	0.0009	0.0006	0.0003
3	0.0008	0.0007	0.0004	0.0001
4	0.0007	0.0006	0.0005	0.0002
5	0.0006	0.0008	0.0008	0.0004
Object points				
6	**0.001**	**0.0012**	**0.0031**	**0.0011**
7	**0.0025**	**0.0026**	**0.0053**	**0.0044**
8	**0.0041**	**0.0065**	**0.0080**	**0.0093**
9	**0.0046**	**0.0047**	**0.0083**	**0.008**
10	**0.0012**	**0.0121**	**0.0046**	**0.0026**
11	**0.0012**	**0.0118**	**0.0037**	**0.0039**
12	**0.0044**	**0.0173**	**0.0080**	**0.0075**

Table 3: Displacement vector of all the monitoring points (in meter)

6. CONCLUSION

A total of five epochs of measurement data were gathered and adjusted using least squares estimation procedure. The measurement epoch was corresponding to the five different loads applied during the axial compression testing. The coordinate differences obtained from lse computation indicate that the displacements vector at some of the target points are to the magnitude of 10 to 17 mm.

This exercise demonstrates the capability of geodetic monitoring survey technique in providing 2D displacement vector information for a sample of concrete slab for civil engineering application.

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BIOGRAPHICAL NOTES

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