An Improved Programme for Deformation Analysis of Vertical Networks

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Key words: Quasi-Static deformation analysis, vertical networks, programming,
S transformation

SUMMARY

Deformation measurements and deformation analysis are the most significant study areas of the engineering surveying. For the determination of vertical deformations, generally the precise leveling method or trigonometric leveling is used. In practical, the precise leveling is in the foreground due to its higher accuracy.

In this study, a Matlab program is written in order to determine the vertical deformation by using precise leveling measurements in quasi-static model. With this program, the outlier measurements can be determined and the deformation analysis can be executed with S-transformation.

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1. INTRODUCTION

The devices and hardwares used in engineering surveying present parallel development with the technology. These developments caused faster collection of accurate data, processing and analyzing them with computer programs and discussion of their results.

In recent years, A. Pfeuffer, O. Heunecke ve W. Welsch spent so much effort for the classification and description of geodetic deformation analysis by depending on the system theory (Heunecke, 1995), (Welsch, 1996), (Pfeuffer, 1994). Heunecke and Welsch presented the similarity between the well-known system hierarchy in the system theory and the geodetic deformation models (Welsch ve Heuncke, 2001).

In this classification, the deformation models are divided into two main groups namely descriptive models and cause-response models. The descriptive models are classified into two subgroups having the names of “quasi-statics” and “kinematics”, and similarly the cause-response models are classified into two subgroups called as “statics” and “dynamics”.

The determination of deformations is mainly formed from two parts. The first is the measurement of deformations and the second is the analysis of these measurements. The deformation measurements were performed with appropriate measuring devices and methods at definite time intervals that are the function of deformation amount and deformation velocity. For instance, the deformation measurements with precise levelling method was performed for the purpose of determining the deformation amounts having vertical annual movements below 0.5-1 mm. The second is the analysis of the measurements. There are many different approaches developed for the deformation analysis. For example, in quasi-static model there are S transformation, θ^2 approach, Hannover approach, etc.

In the analysis of measurements, there were used package programs or computer programs produced by the researchers using the C, C++, Fortran, Matlab,.. etc. compilers. The first option is related with the monetary opportunities of the research institute or public institute and whether the package program about the subject exists or not. The second option is directly related with the programming information of the user.

In this study, a Matlab program was developed for the analysis of one-dimensional deformation measurements performed by a spirit leveling. The deformed points occurring in two different periods can be determined according to the S-transformation by this programme.

2. DEFORMATION ANALYSIS WITH S TRANSFORMATION

The period measurements in the analysis of the deformation measurements are adjusted separately by free adjustment method. The outlier measurements are determined. The homogeneity test is performed for period variance. Before the localization process of the deformation, first of all, it is investigated whether there is deformation or not in the whole of the network by making global congruency test.

If the network geometries observed at times t_1 and t_2 vary (multivariant network), the global congruency test covers only the network sections formed by conjugate points. In other words, the networks measured at times t_1 and t_2 are positioned according to the conjugate points. S transformation matrix is used for this process.

The S transformation matrix is calculated with;

$$S = I - G\,(B^T G\,)^{-1} B^T \qquad (\,B = E\,.\,G\,) \tag{1}$$

equation (Kuang, 1996). I is the unit matrix in Equation (1). And G is the matrix of eigenvectors corresponding to d (defect) number of eigenvalues (λ=0) of matrix N which is the normal equation coefficients matrix. Datum defect number in vertical network is one. G^T vector can be showed equation (2).

$$G^T = \begin{bmatrix} 1 & 1 \cdots\cdots 1 \end{bmatrix} \tag{2}$$

The E matrix named as datum selector matrix in Equation (1) is a diagonal matrix including value "1" corresponding to point heights assigning datum on its diagonal and value "0" for the other values of the matrix. The adjustment results in any *i* datum is transformed into *j* datum with S transformation by using equations (3),(4),(5) (Demirel, 1987).

$$S_j = I - G(B_j^T G)^{-1} B_j^T \tag{3}$$

$$x_j = S_j . x_i \tag{4}$$

$$Q_{xx}^j = S_j . Q_{xx}^i . S_j^T \tag{5}$$

In a network measured in time t_n, let's suppose that the conjugate (datum) points defined as "e" are determined by free adjustment having their coordinates in the first line and the coordinates of other points defined as "b" and the other unknowns at the second line. According to this, the x_i parameter vector related to i datum and the weight coefficients matrix is;

$$x_i = \begin{bmatrix} x_e^i \\ x_b^i \end{bmatrix} \tag{6}$$

$$Q_{xx}^{i} = \begin{bmatrix} Q_{ee}^{i} & Q_{eb}^{i} \\ Q_{be}^{i} & Q_{bb}^{i} \end{bmatrix} \quad (7)$$

divided into sections and then there is passed from *i* datum to *j* datum providing the positioning of network with respect to conjugate points by using Equations (3), (4) and (5). In j datum, the $(Q_{ee}^{j})_1$ ve $(Q_{ee}^{j})_2$ weight coefficients matrix is calculated together with $(x_e^{j})_1$ ve $(x_e^{j})_2$ coordinate unknowns.

The global congruency test of the conjugate points is calculated with;

$$H_o : E(x_e^{j})_1 = E(x_e^{j})_2 \quad (8)$$

$$d_e = (x_e^{j})_2 - (x_e^{j})_1 \quad (9)$$

$$(Q_{dd})_e = (Q_{ee}^{j})_1 + (Q_{ee}^{j})_2 \quad (10)$$

$$R_e = d_e^T (Q_{dd})_e^{+} . d_e \quad (11)$$

and test value F is calculated with the following equation,

$$F = \frac{R_e}{m^2 . h_e} \quad (12)$$

where, $h_e = u_e - d$ is degrees of freedom of R_e.
$F \rangle F_{h_e, f, 1-\alpha}$ is judged to be a deformation at the section formed by the conjugate points of the network. The common variance m^2 that will be valid for 1st and 2nd periods in Equation (12) is calculated with the following equation (İnal and Ceylan, 2003).

$$\mathrm{m}^2 = \frac{f_1 . m_1^2 + f_2 . m_2^2}{f_1 + f_2} \quad (13)$$

Where;
m_1^2 : variance of 1st period
m_2^2 : variance of 2nd period
f_1 : the number of redundant observations of 1st period or degrees of freedom of 1st period
f_2 : the number of redundant observations of 2nd period or degrees of freedom of 2nd period

3.1 The Investigation of Significant Point Movements by Using S Transformation

If there is decided to be any deformation in the network at the end of the global congruency test, the investigation about moving points begins. Thinking each conjugate point is displaced, the x_e^i sub-vector including the conjugate point coordinates of parameters' vector (6) related to the period defined with free adjustment in *i* datum is divided into two sub-vectors namely x_h^i sub-vector including the coordinates of a point that is supposed to be moving and x_s^i sub-vector including the other conjugate (assumed to be constant) point coordinates. Since the parameters related to unconjugate points and the other unknowns are collected in x_b^i vector, the (6) vector and (7) weight coefficients matrix become;

$$x_i = \begin{bmatrix} x_s^i \\ x_h^i \\ x_b^i \end{bmatrix} \quad ; \quad Q_{xx}^i = \begin{bmatrix} Q_{ss}^i & Q_{sh}^i & Q_{sb}^i \\ Q_{hs}^i & Q_{hh}^i & Q_{hb}^i \\ Q_{bs}^i & Q_{bh}^i & Q_{bb}^i \end{bmatrix} \tag{14}$$

Now the network measured in time t_n is positioned with respect to the constant accepted points whose coordinates exist x_s. When this datum is denoted with k, the S_k transformation matrix should be determined from Equation (3) appropriate to (14) differentiation;

$$G = \begin{bmatrix} G_s \\ G_h \\ G_b \end{bmatrix} \quad ; \quad B_k = E_k.G = \begin{bmatrix} G_s \\ 0 \\ 0 \end{bmatrix} \tag{15}$$

and for each period;

$$x_k = S_k.x_i \tag{16}$$

$$Q_{xx}^k = S_k.Q_{xx}^i.S_k^i \tag{17}$$

transformations should be made. The d_s coordinate differences of the points accepted to be constant and their weight coefficients matrix $(Q_{dd})_s$ is calculated with;

$$d_s = (x_s^k)_2 - (x_s^k)_1 \tag{18}$$

$$(Q_{dd})_s = (Q_{ss}^k)_1 + (Q_{ss}^k)_2 \tag{19}$$

equations. R_s value is determined for each point of the x_e sub-vector.

$$R_s = d_s^T.(Q_{dd})_s^+.d_s \qquad (20)$$

If it is decided to be any deformation at any location of the network as a result of the global congruency test, the movement at $(R_s)_{min}$ point is found to be significant and included in the x_b vector.

$$F = \frac{(R_s)_{min}}{m^2.h_s} \qquad (21)$$

If the test magnitude calculated with the above equation is found to be greater than $F_{h_s, f, 1-\alpha}$ limit value, the (14)-(21) calculations will be repeated for the remaining conjugate points. The investigation about of the other moving points will remain continued (Demirel, 1987).

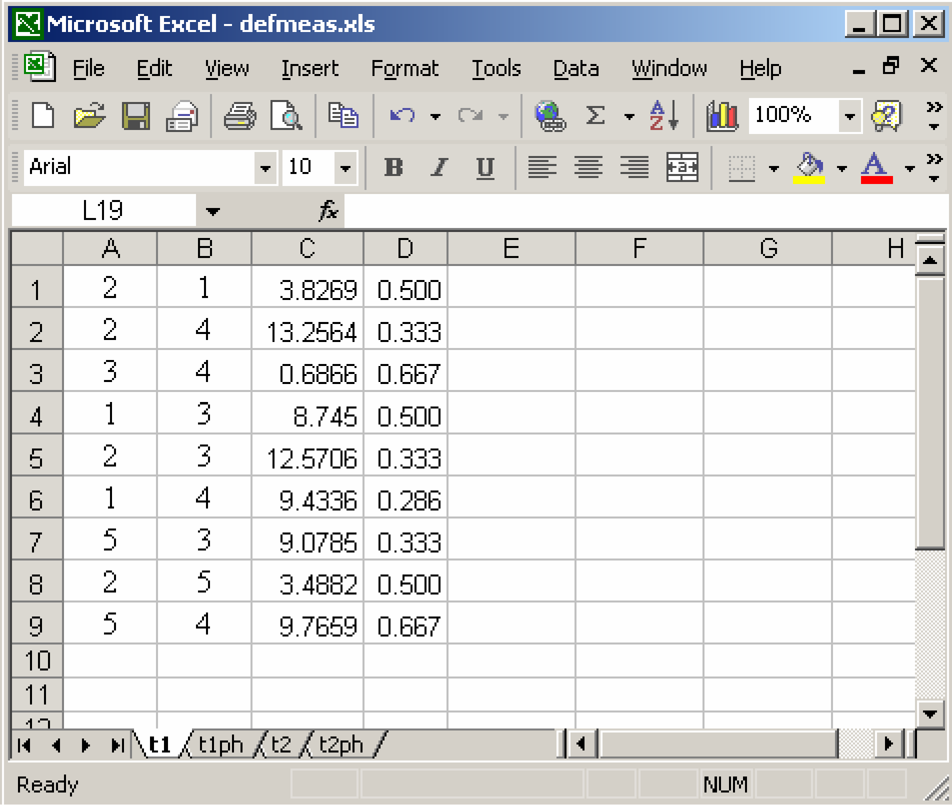
3. THE DEFORMATION ANALYSIS PROGRAM IN 1D NETWORKS

A Matlab program is written for the execution of the deformation analysis. Initially, we wrote another Matlab program that determines whether there exist any outlier measurement or not in the period measurements before beginning the deformation analysis. Since the subject of this study constitutes the deformation analysis, there will be given no information related to the outlier measurement program.

A data file including the deformation measurements is prepared in Microsoft Excel format before the execution of the program we produced(Figure 1). The file is formed from 4 pages namely t1, t1ph, t2, t2ph.

t1 → the page including the 1st period measurements
t1ph → the page including the 1st period network points
t2 → page including the 2nd period measurements
t2ph → the page including the 2nd period network points

The data formats of ”defmeas.xls” data file with respect to pages is explained in Table 1.



	A	B	C	D
1	2	1	3.8269	0.500
2	2	4	13.2564	0.333
3	3	4	0.6866	0.667
4	1	3	8.745	0.500
5	2	3	12.5706	0.333
6	1	4	9.4336	0.286
7	5	3	9.0785	0.333
8	2	5	3.4882	0.500
9	5	4	9.7659	0.667

Figure 1: “defmeas.xls” data file

Table 1: The data format of ”defmeas.xls” data file with respect to pages

	Page name	**1. Column**	**2. Column**	**3. Column**	**4. Column**
1st period	t1	Beginning Point Numbers	Ending Point Numbers	Height difference measurements	Weights
	t1ph	Point Numbers	Point Heights	Datum selector	
2nd period	t2	Beginning Point Numbers	Ending Point Numbers	Height difference measurements	Weights
	t2ph	Point Numbers	Point Heights	Datum selector	

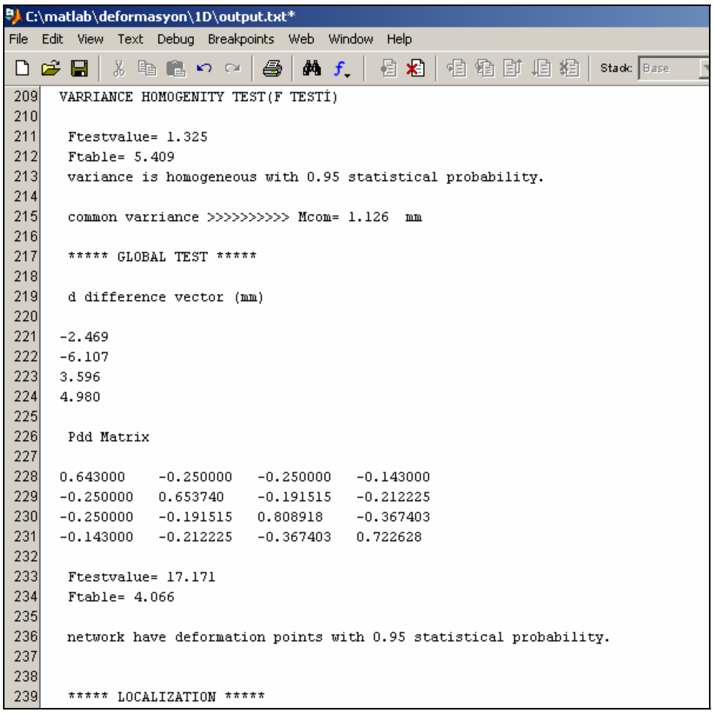
The S-transformation was used in the execution and localization of the deformation analysis of the program. The cause of selecting S-transformation was especially due to its easy programming algorithm when compared with the others. The written program makes analysis according to the following execution steps.

- Reading the data file “defmeas.xls”
- the formation of output files
- Arrangement of required matrix vector names
- Free adjustment of 1st period measurements
- Free adjustment of 2nd period measurements

- the transformation of free adjustment results of the 1st and 2nd periods into partial trace minimum solution by considering the conjugate points
- Applying the homogeneity test on variances and making common variance calculation
- Making global test related to the whole network
- the localization with S-transformation for the determination of the deformed points in the network
- Recording the results to the output files and closing the files.

The execution of the program results in the summarization of analysis results saved in the ”output.txt” file (Figure 2). Output.txt file includes the following information.

- Adjustment results of the 1st and 2nd periods: A is the design matrix, N-1 is the inverse of the normal matrix, x is the unknowns vector, mo is root mean square
- Variance homogenity test
- d_e difference vector and $(Q_{dd})_e^+$ weight matrix both belonging to conjugate points
- Global test
- Localization processes if deformation occurs in the network
- the summarization of deformed points




```
VARRIANCE HOMOGENITY TEST(F TESTİ)

 Ftestvalue= 1.325
 Ftable= 5.409
 variance is homogeneous with 0.95 statistical probability.

 common varriance >>>>>>>>>> Mcom= 1.126  mm

 ***** GLOBAL TEST *****

 d difference vector (mm)

-2.469
-6.107
3.596
4.980

 Pdd Matrix

0.643000    -0.250000   -0.250000   -0.143000
-0.250000   0.653740    -0.191515   -0.212225
-0.250000   -0.191515   0.808918    -0.367403
-0.143000   -0.212225   -0.367403   0.722628

 Ftestvalue= 17.171
 Ftable= 4.066

 network have deformation points with 0.95 statistical probability.


 ***** LOCALIZATION *****
```

Figure 2: “output.txt” file

4. NUMERICAL APPLICATION

The leveling network application in Figure 3 was taken into consideration. The deformation network has multi-variant structure that includes 5 points in the first period and 4 points in the second.

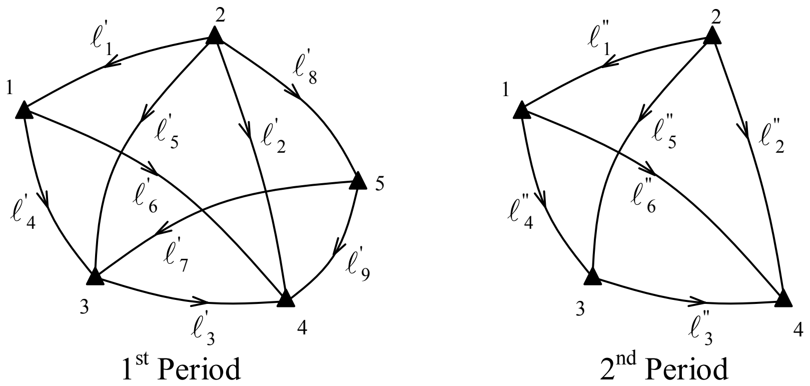


Figure 3: 1 and 2. period deformation networks and its measurements

The average height differences and leveling lenghts in the first and second periods can be seen in Table 2.

Table 2: Height differences and leveling lengths

1st Period		2nd Period		Leveling Lengths (km)
Measurement no.	**Measurements (m)**	**Measurement no.**	**Measurements (m)**	
ℓ'_1	3.8269	ℓ''_1	3.8300	2.00
ℓ'_2	23.2564	ℓ''_2	23.2652	3.00
ℓ'_3	0.6866	ℓ''_3	0.6893	1.50
ℓ'_4	18.7450	ℓ''_4	18.7517	2.00
ℓ'_5	22.5706	ℓ''_5	22.5806	3.00
ℓ'_6	19.4336	ℓ''_6	19.4390	3.50
ℓ'_7	9.0785			3.00
ℓ'_8	13.4882			2.00
ℓ'_9	9.7659			1.50

The approximate heights of points before adjustment and the adjustment information are given in Table 3 and Table 4 respectively.

Table 3: Approximation heights

Point Number	Approximation Heights (m)
1	50.00
2	46.17
3	58.75
4	59.43
5	49.66

Table 4: Adjustment informations

	1st Period	2nd Period
Measurement number	9	6
Unknown number	5	4
Datum deficiency	1	1
Freedom	5	3
Root mean square (mm)	1.1	1.2
Outlier	Not existing	Not existing

According to the deformation analysis results;

- Variances were found homogeneous and common root mean square is calculated as Mort= ± 1.13 mm.
- The deformation in the network was determined after the global test
- The network points of 2 and 1 deformed due to localization. The localization process steps according to Rs_{min} results can be seen in Table 5.

Table 5: Localization results

Point Number	Rs	
	1st Localization	2nd Localization
1	60.92	**1.08**
2	**25.15**	-
3	55.11	22.67
4	43.93	17.31

5. CONCLUSION

The deformation measurements and analysis are the most significant study areas of engineering surveying. The devices and hardwares used in engineering measurements present parallel development with the technology. These developments caused faster collection of accurate data, processing and analyzing them with computer programs and discussion of their results.

In the analysis of measurements, there were used package programs or computer programs produced by researchers using C, C++, Fortran, Matlab,.. etc. compilers. The first option is related with the monetary opportunities of the research institute or public institute. The second option is directly related with the programming information of the user.

In this study, a Matlab program was developed for the analysis of one-dimensional deformation measurements performed by a spirit leveling . S-transformation algorithm was used for the development of the program codes. As a result, the analysis of deformation measurements should be performed by a researcher or an engineer who codes them in an appropriate algorithm and compiler. The selected algorithm and compiler directly affects the coding period of the program.

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BIOGRAPHICAL NOTES

Cemal Ozer Yigit is a research assistant at Selcuk University in Turkey. He has been academic staff at the university since 2000. His research interests focus on deformation measurement and analysis, statistic and programming.

Dr. Cevat Inal is a Professor at Selcuk University in Turkey. He has been academic staff at the university since 1983. His research interests focus on high precision surveying techniques, surveying applications, and engineering surveying applications, geodetic networks adjustment, high precision surveying instruments, deformation, and height determining studies.

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