DEFORMATION MONITORING BY USING THE COMBINATION OF GEOTECHNICAL AND GEODETIC OBSERVABLE

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ABSTRACT

Large structures such as dams undergo deformation. Deformation monitoring is required to ensure the dams are secured during its operational life. Among the various scheme of monitoring, the deformation monitoring via geodetic method can be applied to obtain the status of displacement vector of the surface object points under investigation. Geotechnical observables are complementary to the geodetic network observables for the deformation modeling purpose. Geodetic network provides the absolute displacement vector of the object points on the surfaces of the body under investigation while the geotechnical measurement provides the relative displacement inside the body. This paper describes the combination scheme of the geodetic and geotechnical observables to determine the deformation model. The whole scheme of the computer program to handle the deformation analysis is also described. The preliminary results of some modules of the program are presented, followed by some important recommendations.

Keywords: deformation analysis, geometrical analysis, monitoring survey, deformation modeling.

1. GEOTECHNICAL VS GEODETIC OBSERVABLE

Geotechnical observables are complementary to the geodetic network observables for the deformation modeling purpose. Geodetic network provides the absolute displacement vector of the object points on the surfaces of the body under investigation while the geotechnical measurement provides the observable inside the body. Even the geodetic method can determine the deformation model of the whole body; it is actually an extrapolative manner if the model is applied to the points inside the body because there is no data inside the body to develop the model. This is the main reason why geotechnical are complementary to the geodetic network data. The more complete properties of the geotechnical and geodetic observables are listed in Table 1 below.

Table 1: The Properties of the geotechnical and geodetic observables

No.	Geodetic	Geotechnical
1.	Provide absolute displacements vector, spatial trend can be figured.	Provide local movement, comprehensive spatial trend is not easy.
2.	Object points are on surface of the object. Observables are interconnected, network quality control is facilitated.	Object points on surface and inside the body of the object. Observables are not interconnected: no inter-observable controlling is facilitated.
3.	Deformation model is extrapolative in nature.	Geotechnical observables complement to avoid the extrapolative model.
4.	Block translation and linear and non linear deformation can be modeled.	Block translation can not be modeled.
5.	Continuous and telemetry data recording are still under development. Time-series trend is provided discretely. Anomaly behaviors of object can not be detected earlier.	Continuous and telemetry data recording have been in advanced. Time-series trend is provided continuously. Anomaly behaviors of object can be detected earlier.

The geotechnical data is divided into three groups according to its purpose, mainly (Chrzanowski, 1986):

1. Determination of physical properties of the deformable material.
2. Determination of acting forces (loads) and internal stresses.
3. Determination of change in dimension and shape (geometrical deformation).

For static deformation (i.e. the research focus), the third group of data is of direct interest. This group of geotechnical data can be classified according to its relationship to the relative displacement, i.e. (Chzranowski, 1986; Secord, 1985; Chen 1983):

(1) change of tilt/inclination
(2) change of strain
(3) change of distance
(4) change of displacement along x or along (x, y) (lateral movement)
(5) change of displacement along z axis (vertical movement).

Table 2 below presents the various geotechnical instruments that can provide the geometrical deformation observables.

The most common geotechnical instruments sense/measure electrically. Electrically, the small change in observation can be transformed into the small change of resistance in Resistance Bridge. The change of resistance then can be converted into digital/analog readout. However, the electrical sensors are very sensitive to the temperature (Chrzanowski, 1989; http://zone.ni.com/devzone/conceptd.nsf/webmain). The temperatures are cyclic over the year. Temperature fluctuations influence the electrical component of the instrument and then influence the readout of the electrical sensor. Thus, it is important to figure out the thermal fluctuation of the geotechnical readout/measurement.

Table 2: Geotechnical Instrumentation and the Observable

No.	Instrument	Quantity Measure (Observable)				
		Lateral movement (dx,dy)	Vertical movement (dz)	Change Strain μ	Change Tilt Angle (β)	Change of Distance s
1	Extensometer (Tape Extensometer, Rod Extensometer Multirod Extensometer)	√	√			√
2	Pendulum: -Hanging Pendulum -Inverted Pendulum	 √ √				
3	Inclinometer -Vertical Borehole Inclinometer, -Horizontal Inclinometer	 √	 √			
4	Clinometer: (Uni-axial Clinometer, Bi-axial Clinometer)		√		√	
5	Tiltmeter: (Uni-axial and Bi-axial)				√	
6	Strainmeter, strain gauge			√		
7	Settlement gauge, Hydrostatic Levelling		√			
8	Deflectometer	√	√			

In static deformation analysis, deformation between two epochs is considered as linear in time. As both geotechnical and geodetic data have to be synchronized with the linear assumption over time, the parameter of linear trend of the time series of geotechnical data is very important.

The corrected/compensated outcome of the geotechnical observable can be obtained by the cyclic regression curve fitting. The typical regression model applied is (Chrzanowski, 1989):

$$y\ (t) = a_1 \cos (2\pi\ t) + a_2 \sin (2\pi\ t) + a_3\ t + a_4 \qquad (1)$$

Due to the annual cyclic properties of earth environment, t represents time in years. y is the value of the readout given by geotechnical instrument at a station of observation. The parameters of regression model (a_1 , a_2 , a_3 , a_4) can be obtained both by applying L_2-norm or L_1-norm estimation. Linear trend parameter, a_3, is then used to synchronize the geotechnical data with geodetic data according to the static deformation model.

The estimated of the parameters is formulated as below:

$$y + v = A\ x, \qquad (2)$$

where:

$$\mathrm{y} = \begin{bmatrix} y(t_0) \\ y(t_1) \\ . \\ . \\ . \\ y(t_n) \end{bmatrix};\quad \mathrm{v} = \begin{bmatrix} v(t_0) \\ v(t_1) \\ . \\ . \\ . \\ v(t_n) \end{bmatrix};\quad \mathrm{A} = \begin{bmatrix} \cos 2\pi t_0 & \sin 2\pi t_0 & t_0 & 1 \\ \cos 2\pi t_1 & \sin 2\pi t_1 & t_1 & 1 \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ \cos 2\pi t_n & \sin 2\pi t_n & t_n & t_n \end{bmatrix};\quad \mathrm{x}^T = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

The L_2-norm estimation of the Eq. (2) provides the parameters x and the covariance matrix Q_x,

$$x^T = (A^T WA)^{-1} A^T y. \tag{3}$$

$$Q_x = (A^T W A)^{-1} \tag{4}$$

where W is the weight of the observation.

To overcome the sensitivity of least squares to the outlier, the linear equation (2) is solved by L_1-norm estimation (least absolute). More detail theory of the L_1-norm estimation and its application to the over determined equation system of Eq. (2) can be found in Branham (1990) and Yul (2000).

The graphical presentation of the regression can be given as shown in Figure 1 below:

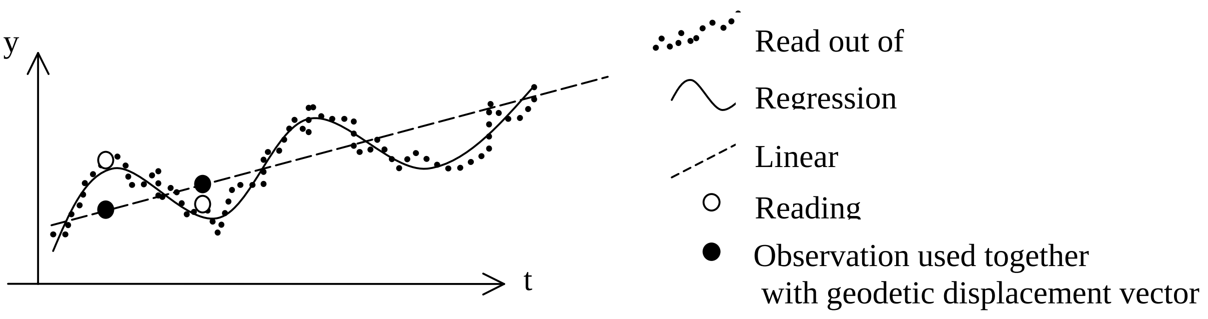


Figure 1: Linear trend in cyclic regression and corrected outcomes of the geotechnical data

2. GEODETIC OBSERVABLE AND ITS QUALITY CONTROL

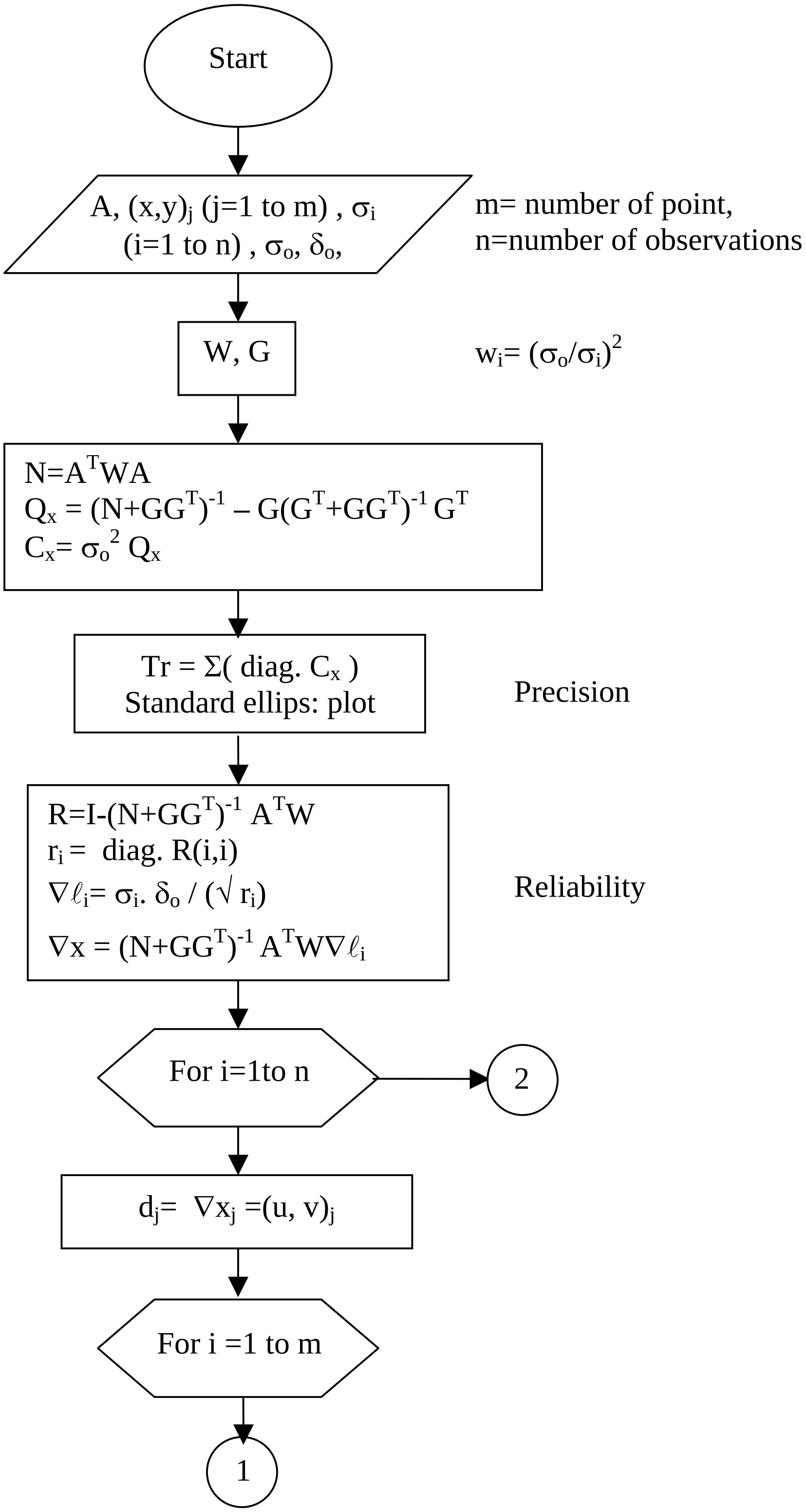
The episodic observations of geodetic network provide the displacement vector d of the discrete network points, and the variance-covariance, Q_d. Displacement vector d is the coordinate differences between epochs based on common datum definition. Coordinates of each epoch are estimated quantities corresponding to mathematical model relating the geodetic observables and the coordinates of the points of the network.

The uncertainty of the observable and the imperfection of the mathematical model involved will affect the quality of the analysis performed. The quality control should be done to treat this uncertainty/imperfection in order to achieve the valid results for certain monitoring purpose. Taking beneficial of the L_2-norm estimation, it is possible to measure the quality or performance of the network even at design stage.

The uncertainty due to the random errors is controlled by the use of precision reflected by variance-covariance matrix. The propagation of random errors of the observable to the unknown parameter can be controlled at design stage, and can be assessed by the use of the statistical tests. Bias, as a result of imperfection of mathematical model or the existence of gross errors can be controlled by the use of reliability and/or robustness analysis concept. The concept of robustness measure is developed by the UNB research group. Details on the robustness concept and its implementation are given in Vanicek et.al. (1990), Vanicek et.al (2001), and Amiri (2001).

The reliability concept is traditionally used to control the bias and its influence to the unknown parameters. The disadvantage of reliability measure is of datum dependent. This disadvantage has been enhanced by the theory of robustness analysis. Robustness analysis is a merging between reliability and strength of geometry analysis and it is datum-independent. Figure 2 shows the scheme of quality control of the geodetic network.

Any gross errors lead to the artificial movement, while L_2-norm estimation is not so robust for gross error detection, moreover if multiple gross errors exist. It is due to the sensitivity of L_2-norm estimation to the gross errors. It should be emphasized that the results of L_2-norm estimation is only valid if no gross errors exist. On the other hand L_1-norm estimation is robust even multiple gross errors exist. The application of the L_1-norm estimation is now easier after the lack of computation for more than three centuries has been solved by Barradole algorithm. The computing procedure of L_1-norm estimation for gross error detection of geodetic network has been implemented by Yul (2000). The detailed explanation of the concept, algorithm of the L_1-norm estimation can be found in Branham (1989), Barradole & Roberts (1973).


Start
A, $(x,y)_j$ (j=1 to m) , σ_i (i=1 to n) , σ_o, δ_o,
m= number of point,
n=number of observations
W, G
$w_i = (\sigma_o/\sigma_i)^2$
$N=A^TWA$
$Q_x = (N+GG^T)^{-1} - G(G^T+GG^T)^{-1} G^T$
$C_x = \sigma_o^2 Q_x$
$Tr = \Sigma($ diag. $C_x)$
Standard ellips: plot
Precision
$R=I-(N+GG^T)^{-1} A^TW$
$r_i =$ diag. R(i,i)
$\nabla\ell_i = \sigma_i . \delta_o / (\sqrt{r_i})$
$\nabla x = (N+GG^T)^{-1} A^TW\nabla\ell_i$
Reliability
For i=1to n
2
$d_j = \nabla x_j = (u, v)_j$
For i =1 to m
1

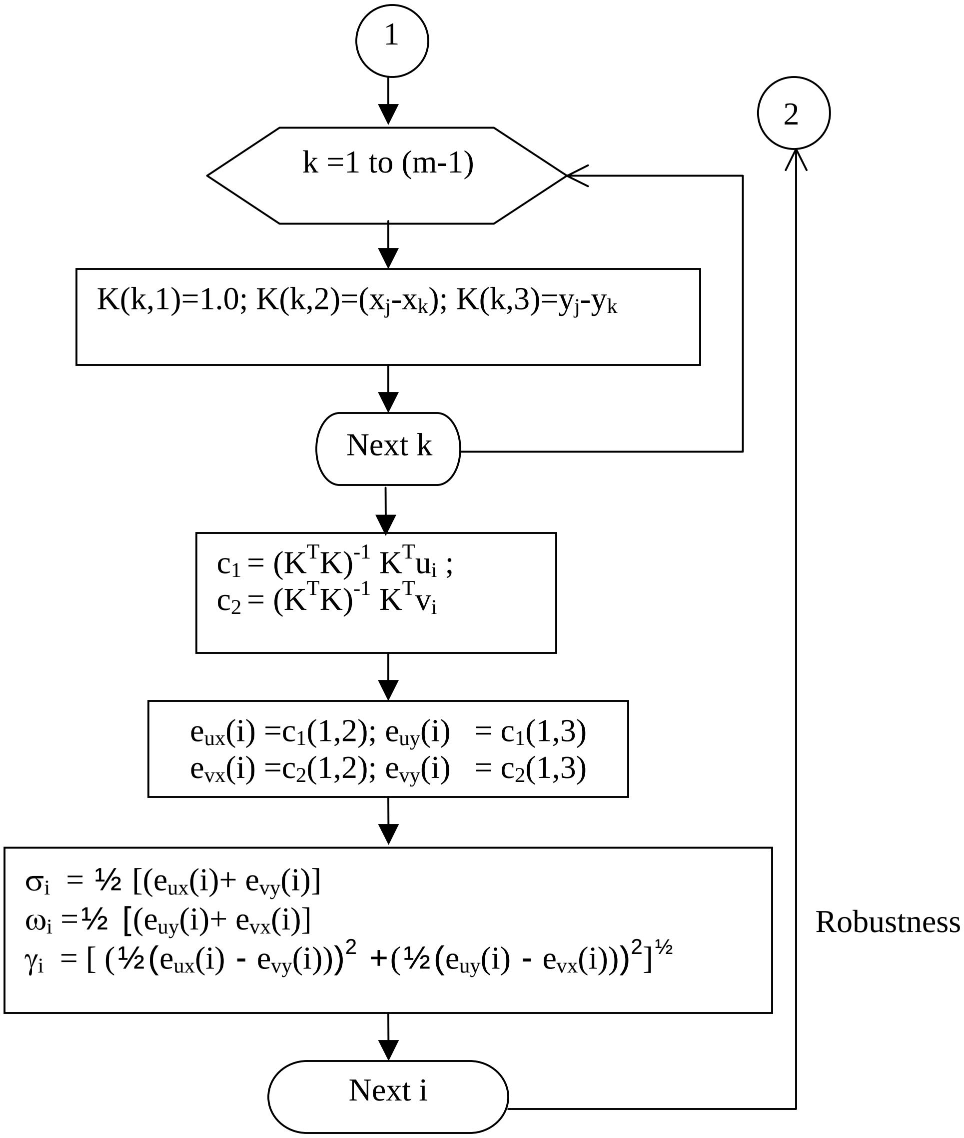


Figure 2: The Scheme of Quality Control for Geodetic network

Instead of minimizing the sum of residual squares as used in L_2-norm, the criteria of L_1-norm estimation is to minimize the sum of the absolute of residuals. Computation algorithm of L_1-norm estimation is actually based on the application of standard Linear Program, then the simplex algorithm can be applied to obtain the solution/estimation.

The simplex algorithm applied in L_1-norm estimation will group the observation in two groups: the first group is error-free observation with zero residuals and the second is the remaining observations that may contain any errors including gross errors. Further testing incorporates both global and local tests (Yul, 2000).

3. DEFORMATION MODELING

In general the deformation model that relates geodetic data and geotechnical data can be written as:

$$d = B\ c \tag{5}$$

$$l_g = AB'\ c \tag{6}$$

where d is displacement vector provided by geodetic observation, *l* is the geotechnical data, and c is the parameter of the model. In more compact form, Eq. (5) and Eq.(6) can be written as:

$$l = Bc \tag{7}$$

Displacement vector of two epochs with similar minimum datum constraint and its covariance matrix Q_d can be computed with the application of L_2-norm estimation as discussed by Chen (1983), Secord (1985), Caspary (1987), Halim (1995), Kuang (1996), and Ranjit (1999). More detailed derivation of Eq. (5) and Eq. (6) can be found in Secord (1985) and Chen (1983).

For the purpose of combination of geodetic data and geotechnical data as given by Eq. (5) and Eq. (6), the geotechnical data have to be time-synchronized with geodetic data through Eq. (1), (2), (3) and (4). For static deformation analysis, the parameter of linear trend, a_3 in Eq. (1) is required for synchronization. The geodetic data for combination in Eq. (5) and (6) is the data obtained by Eq. (3) and (4).

The flowchart shown in Figure 3 is the whole procedure for deformation modeling purpose. The geodetic network, at design stage can be analyzed to determine the network performance corresponding to the deformable object to be investigated. The network performance (or quality measures) includes reliability, sensitivity, precision and robustness.

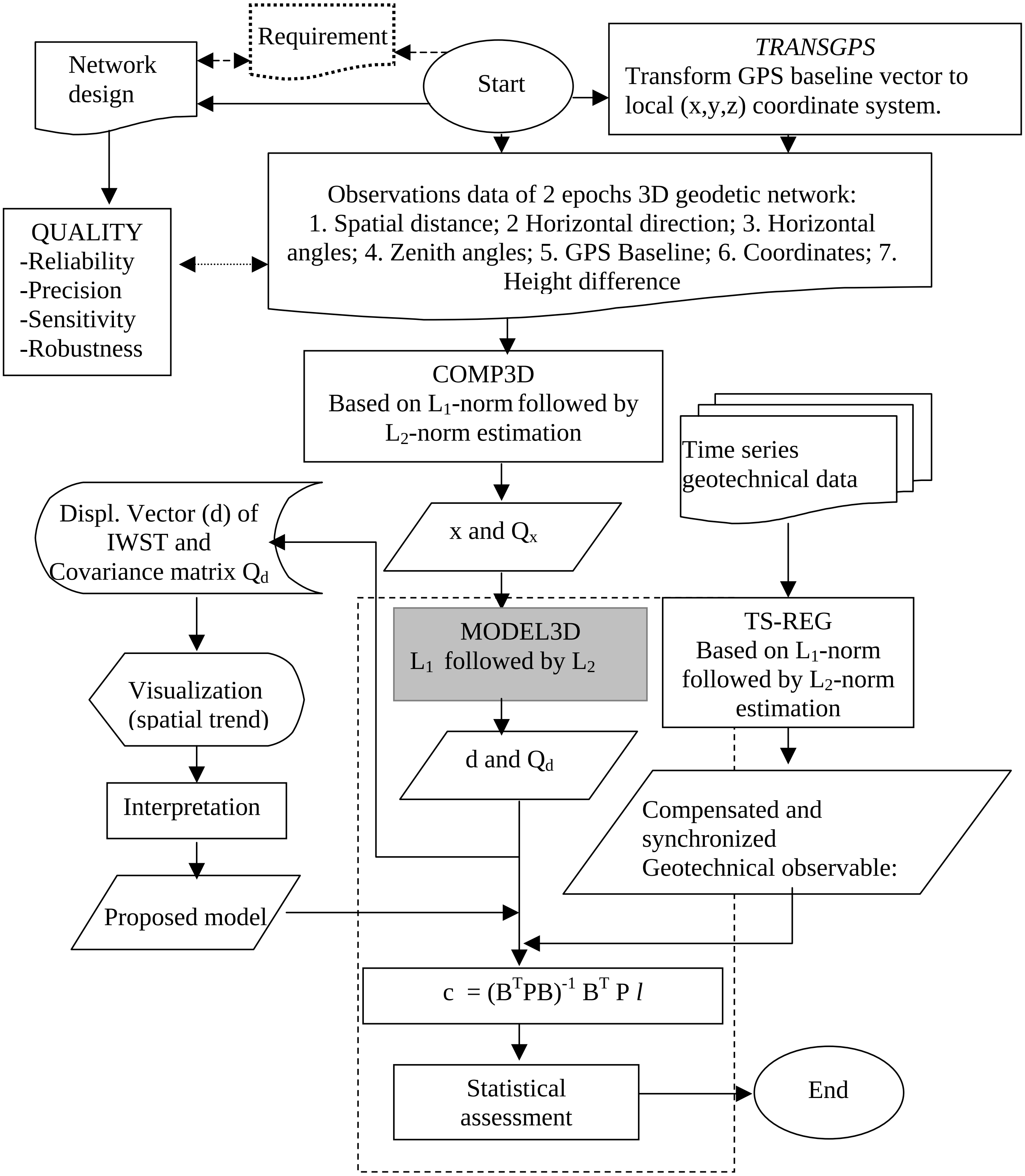


Figure 3. The Scheme of deformation modeling using geodetic and geotechnical observable, based on L_1-norm and L_2-norm estimation.

4. PRELIMINARY RESULTS

Some preliminary results discussed in this paper is the module of COMP3D and TS-REG.

4.1 COMP3D

The three dimensional geodetic network processed using COMP3D (for the time being is based on L_2-norm estimation and to be completed with L_1-norm) is shown in Figure 4.

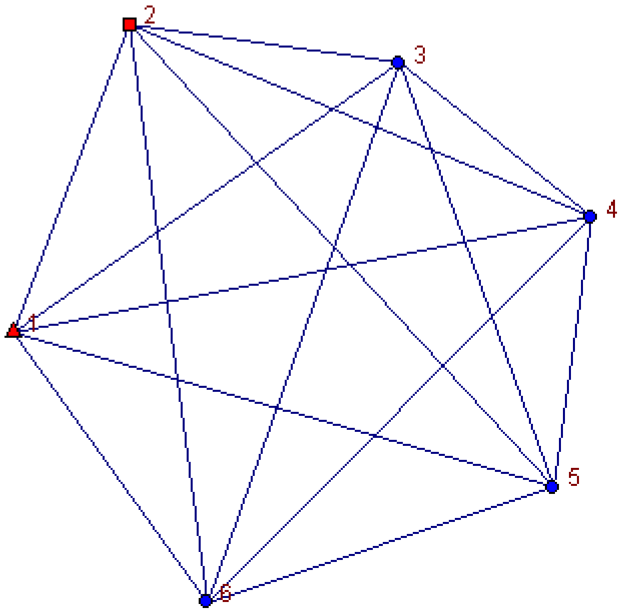


Figure 4. Three Dimensional Geodetic Network.

Table 3: Provisional Coordinates

Station	PROVISIONAL COORDINATES			ADJUSTED COORDINATES			Datum definition		
							fixx	fixy	fixz
1	2600.000	1200.000	120.000	2600.0000	1200.0000	120.0000	1	1	1
2	3000.000	1350.000	140.000	2999.9999	1349.9497	139.9906	0	0	0
3	2950.000	1700.000	80.000	2950.0583	1699.9604	79.9945	0	0	0
4	2750.000	1950.000	90.000	2750.0828	1949.9946	89.9945	0	0	0
5	2400.000	1900.000	150.000	2400.0612	1900.0153	149.9914	0	0	0
6	2250.000	1450.000	100.000	2250.0355	1450.0271	99.9937	0	0	0

Table 4: Observations, residuals and standardized residuals.

No.	Observation (meter for distance & deg-min-second for angle)	Residuals (meter for distance & second for angle)	standardized residuals	From-to or At-from-to	code
1	427.6498	.000113	.0543	1-2	0
2	611.6396	-.001048	.3121	1-3	0
3	765.4520	.000231	.0917	1-4	0
4	728.6245	.001936	.5539	1-5	0
5	430.5693	-.001112	.4777	1-6	0
6	320.3240	-.000197	.0670	3-4	0
7	589.4223	-.000199	.0593	3-5	0
8	743.5707	.000849	.2840	3-6	0
9	358.6120	-.001863	.4030	3-2	0
10	476.9611	.005248	1.0974	5-6	0
11	814.0017	-.000023	.0069	5-2	0
12	358.6164	-.000318	.1195	5-4	0
13	69-27- 1.31	-.330356	.0782	1-2	1
14	34-59-54.83	.265045	.0603	1-3	1
15	11-18-57.44	.485099	.1108	1-4	1
16	344- 3- 33.79	.645478	.1462	1-5	1
17	305-32-37.17	-1.065266	.2543	1-6	1
18	325-32-53.52	.595451	.1241	1-2-3	2
19	336-19- 2.61	.220104	.0456	2-3-4	2
20	332-44-36.34	.170428	.0351	3-4-5	2
21	321-29- 3.39	-1.720693	.3598	4-5-6	2
22	80-22- 9.22	.692846	.4141	3-2	3
23	96- 1- 2.16	1.800444	1.3036	5-6	3
24	19.9908	-.000191	.0919	1-2	6
25	-59.9952	-.000890	.3617	2-3	6
26	10.0001	-.000109	.0527	3-4	6
27	59.9970	-.000072	.0343	4-5	6
28	-49.9990	.001255	.5596	5-6	6
29	20.0063	.000006	.0027	6-1	6

Simulated data, modified from Halim (1995)
Code 0= spatial distance; 1=bearing; 2= horizontal angle; 3=zenith angle; 4=3D-baseline vector; 5=3D coordinates; 6=height differences.

Statistical analysis of the network:
A posteriori variance = .14160
Standard deviation= .37630

One-tailed Chi-squares test with 95% confidence level: pass
statistic value = 1.982, while upper-bound= 26.119
Critical value of Normal test of Baarda= 1.96

The L_2-norm estimation results (Table 3 and Table 4) passed both global (Chi-squares) and local (Baarda) tests, indicating no gross errors in the observation. For checking purpose, results from COMP3D were found to be very close to the commercial software STAR*NET (Table 5). In addition to the adjusted coordinates and covariance matrices, COMP3D produces special file for deformation analysis purpose (Table 6).

Table 5: COMP3D vs STAR*NET

Sta.	COMP3D			STAR*NET			STAR*NET-COMP3D		
	x	y	z	x	y	z			
1	2600.0000	1200.0000	120.0000	2600.0000	1200.0000	120.0000	0.0000	0.0000	0.0000
2	2999.9999	1349.9497	139.9906	3000.0000	1349.9490	139.9891	0.0001	0.0007	0.0015
3	2950.0583	1699.9604	79.9945	2950.0576	1699.9607	79.9854	0.0007	-0.0003	-0.0009
4	2750.0828	1949.9946	89.9945	2750.0809	1949.9944	89.9838	0.0017	0.0002	0.0017
5	2400.0612	1900.0153	149.9914	2400.0591	1900.0141	149.9791	-0.0021	0.0012	0.0123
6	2250.0355	1450.0271	99.9937	2250.0360	1450.0295	99.9954	0.0005	-0.0024	-0.0017

Table 6 The Output of COMP3D for deformation analysis purpose

No.	Quantities	Value	Remarks
1	A Posteriori variance factor	.141599	
2	Degree of freedom	14	
3	Number of station	6	
4	Datum defect	3	
5	Datum defect	0 0 0 1 1 1 1	Tx, Ty, Tz, Rx, Ry, Rz, S

4.2 TS-REG

TS-REG aims to facilitate the synchronization of the geotechnical data with geodetic data. The parameters provided by TS-REG are the coefficients of cyclic polynomial. Table 7 is the simulated data of borehole extensometer in Chrzanowski et.al (1989). The test using this data shows that the parameter resulted by TS-REG, as shown in Table 8, is relatively closed to the known parameters.

The statistical analysis shows that, as a result of L_1-norm estimation, the sum of absolute residuals is 16.078 with average 1.072. The global Chi-squares test passed at 95% confidence level (critical value is 24.998 while the statistic to be tested is 17.428), and no outliers were found.

Table 7 The simulated geotechnical data (borehole extensometer), graphically extracted from Chrzanowski et.al (1989).

No.	date	month	year	observation	Std. deviation
1	0	3	1985	0.912	0.001
2	15	4	1985	1.374	0.001
3	0	6	1985	1.653	0.001
4	15	7	1985	1.737	0.001
5	0	9	1985	1.639	0.001
6	15	10	1985	1.402	0.001
7	0	12	1985	1.090	0.001
8	15	1	1986	0.778	0.001
9	0	3	1986	0.542	0.001
10	15	4	1986	0.444	0.001
11	0	6	1986	0.528	0.001
12	15	7	1986	0.809	0.001
13	0	9	1986	1.272	0.001
14	15	10	1986	1.873	0.001
15	0	12	1986	2.549	0.001
16	15	1	1987	3.224	0.001
17	0	3	1987	3.824	0.001
18	15	4	1987	4.285	0.001
19	0	6	1987	4.564	0.001

Table 8: The parameter of cyclic-curve fitting provide by TS-REG.

Parameters	TS-REG		Chrzanowski et.al (1989)
	L_1-norm	L_2-norm	
a_1	.9121	9127	na
a_2	.9122	.9120	na
a_3	1.4550	1.4558	1.4549
a_4	-.0001	-.0007	na.

a_1, a_2, a_3, a_4 are referred to Eq. (1).

5. CONCLUSION REMARKS

The issues of the combination of methods to study deformation have been considered to enhance the understanding of deformation behaviors. The combination of two type of sensor grouped traditionally as geodetic sensor and geotechnical sensor has been discussed. This combination is complementary in nature. Also, the combination of the estimation approach is also complementary and need to be applied. This paper is part of the research focusing on the possibility of combination of any approach for deformation modeling. Specific program is absolutely needed to be developed. Two modules of the program, i.e. (i) the three-dimensional geodetic adjustment called as COMP3D and (ii) cyclic regression called as TS-REG for time-synchronizing the geotechnical data with geodetic data have been developed and tested. The simulation tests of the two modules show good agreement. Currently, one complete package for deformation modeling is still under development.

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