DAM MONITORING NETWORK AND DEFORMATION STUDIES

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Abstract

Deformation of concrete dam is a complex process. For large deformation structures such as concrete dam, one should consider the interaction between the structure and the underlying soil and rock strata, influence water load on the structure and the foundation rock. Safety of dams depend on the proper design, construction and monitoring of actual behavior during the construction and during the operation of the structure. This paper describes the methodology applied in deformation monitoring network, using two dimensional survey network. In this paper, the configuration of the monitoring survey network and observations within the network are given. The observation involved two-epoch data set. The adjustment of separate epochs and the localization of movements between epochs are outlined. Finally, recommendations on methodology are given. This methodology are generally applicable to any situation in which movement are to be monitored by means of a survey network.

1.0 Introduction

One of the great engineering structures made by human is dam. Human used water to generate electricity power and for water reservoirs. Dam was used to produce clean energy and human purpose. Dam is a massive structure and most complex engineering structure. The dam has to be designed for all operational cases. Warning of any suspicious movement can usually be obtained well in advance, provided that the measurement are sufficiently sensitive.

The techniques of monitoring are very closely integrated with those of geodetic surveying, and are increasingly applied in civil engineering project. Geodetic monitoring measurement method offered economic, flexibility and very accurate for viewing global picture of deformation. Usually, monitoring work need cooperation between geodesist and civil engineer. The civil engineer has specified instrument such as strain meter, inclinometer, peizometer and etc.

Deformation analysis by geodetic method mainly consists of two-step analysis via independent adjustment of each epoch and then followed by deformation detection between two epochs. Nowadays, there are two types of techniques for deformation detection: rigorous method and non-rigorous method (direct coordinate differences). Rigorous method gives better information and interpretation than non-rigorous method. The important output from deformation detection is the trend of movement (displacement).

This paper deals and discuss about dam deformation monitoring network and analysis. The data was taken from one of monitoring scheme in Malaysia. The non-rigorous method has been applied for Klang Gate Monitoring network. Two techniques have been applied for estimating the movement and deformation modeling namely congruency testing and iterative weighted similarity transformation (IWST) (Caspary, 1987; Chen, 1983).

2.0 The Method

2.1 Network Adjustment

The measured data (e.g., directions and distances) are related to the parameter (coordinates) by mathematical relationship called the functional model and expressed as (Cooper, 1987; Harvey, 1990);

$$l = f(x) \tag{1}$$

where, ***l*** is the vector of observations and ***x*** is the vector of parameter to be estimated. Equation (1) generally is non-linear and it needs to be linearized using Taylor's theorem whereby the observation equation is written as;

$$\hat{v} = A\hat{x} + b \tag{2}$$

where, $\hat{v}$ is the vector of residuals, ***A*** is the design matrix, $\hat{x}$ is the vector of corrections to the approximate value and *b* is the misclosure vector. The normal equation with a full rank can be written as;

$$N\hat{x} + U = 0 \tag{3}$$

and solution for $\hat{x}$;

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

where, $P = \sigma_0^2 \sum_l^{-1}$, weight matrix. In general, least square estimation suffers from rank deficiency due to configuration or datum defect. As a solution, datum defect are overcome by means of constraints. Normally, the common choices of datum for the monitoring network are minimum constraint, minimum trace and partial minimum trace. In this particular work, the method of minimum constraint was chosen as datum definition.

During least square adjustment, other important aspects that need to be considered are global test (Chi-square) and local test (TAU test). The global test (chi square) examines the null hypothesis; $H_0 : \hat{\sigma}_0^2 = \sigma_o^2$, test passed or $H_a : \hat{\sigma}_0^2 \neq \sigma_0^2$.test failed

For local test, Pope method is commonly adopted. The null hypothesis for the local test becomes; $H_o : E\left(\hat{v}_i^*\right) = 0$ or $\hat{v}_i^*$ free from gross error or $H_a : E\left(\hat{v}_i^*\right) \neq 0$ or one residual effected by gross error. For further detailed the readers are referred to Caspary (1987), Halim (1995), Ranjit (1999), Khairulnizam (2004)

2.2 Deformation Analysis

2.2.1 Congruency Testing

The objective of a congruency test is to detect whether or not the point group in a deformation network has remained stable. The test is based on F-statistic, which requires the computation of pooled variance of the epoch and statistical test. The *a posteriori* variance factors of both epochs are then tested for their compatibility. Basically the adopted procedure of congruency testing consists of the following (Cooper, 1987; Halim, 1995; Ranjit, 1999; Khairulnizam, 2004):-

a) Transformation of the displacement vector and its cofactor matrix for both epoch into a common datum.

During congruency testing, it is important that displacement vector ***d*** and cofactor matrix Q_d are referred to the same datum. The displacement vector and its cofactor matrix can be computed as:-

$$d_1 = \hat{x}_2 - \hat{x}_1 \quad (5)$$

$$Q_{d1} = Q_{\hat{x}_1} + Q_{\hat{x}_2} \quad (6)$$

S-transformation have been applied to transform matrix ***d*** and Q_d into a common datum definition (either minimum trace or partial minimum trace) (Caspary, 1987; Cooper, 1987; Halim, 1995; Khairulnizam, 2004):-

$$S = [I - G\left(G^T WG\right)^{-1} G^T W]d \quad (7)$$

$$d_2 = Sd_1 \quad (8)$$

$$Q_{d_2} = SQ_{d_1}S^T \quad (9)$$

where; *I* is identity matrix and W is weight matrix and

$$G^T = \begin{bmatrix} 1 & 0 & 1 & 0 & & 1 & 0 \\ 0 & 1 & 0 & 1 & & 0 & 1 \\ y_1^0 & -x_1^0 & y_2^0 & -x_2^0 & \cdots\cdots\cdots & y_m^0 & -x_m^0 \\ x_1^0 & y_1^0 & x_2^0 & y_2^0 & & x_m^0 & y_m^0 \end{bmatrix} \quad (10)$$

where x_i^0, y_i^0 are the coordinate of point p_i which reduce to the center of gravity of the network.

b) Determination of stable datum points by congruency testing;

$$\omega = \frac{\Omega}{\left(h \bullet \hat{\sigma}_o^2\right)} = \frac{d_2'^T Q_{d_2}'^{+} d_2'}{\left(h \bullet \hat{\sigma}_0^2\right)} \sim F\left(\alpha, h, \partial f\right) \quad (11)$$

where;

$d_2' =$ displacement vector and its cofactor matrix of the common datum point in both epoch.

$Q_{d_2}{}' =$ cofactor matrix for displacement vector d_2'.

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

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

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

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

$h =$ rank $(Q_{d_2}') = (2n - d)$ for 2D network with *n* number of common point and *d* number of datum defect.

c) Localization of deformation through single point test, S-transformation and congruency testing.

d) Final testing on all common points by single point test.

$$T_j = \frac{\Omega}{2 \bullet \hat{\sigma}_o^2} = \frac{d_{3j}^T Q_{d_{3j}}^{-1} d_{3j}'}{2 \bullet \hat{\sigma}_o^2} \sim F(\alpha, 2df) \qquad (12)$$

2.2.2 Iterative Weighted Similarity Transformation (IWST)

The iterative weighted similarity transformation (IWST) was developed at University of New Brunswick, Canada (UNB) (Chen, 1983). The IWST method based on S-transformation (equation 7) as below (Chen, 1983; Ranjit, 1999):

$$S = [I - G(G^T W^{(k)} G)^{-1} G^T W^{(k)}]d = S^{(k)} d^{(k)} \qquad (13)$$

In the first transformation (k=1) the weight matrix is taken as identity $(W^{(k)} = I)$ for all the common points, then in the (k + 1) transformation the weight matrtix is defined as:

$$W^{(k)} = diag\left\{\frac{1}{\left|d_i^{(k)}\right|}\right\} \qquad (14)$$

The above weighting scheme is only applied on the common datum point whilst for the object points the weight is set by zero. The iterative procedure continues until the absolute differences between the successive transformed displacements of all the common points (e.g. $\left|d^{(k+1)} - d^{(k)}\right|$) are smaller than a tolerance value ∂ (say 0.0001 meter). For further detail on robust estimation (rigorous method) are given in Chen, (1983) and Ranjit, 1999).

In the last iteration, the cofactor matrix of the displacement vector is computed as: -

$$Q_d^{(k+1)} = S^{(k)} Q_d (S^{(k)})^T \qquad (15)$$

3.0 The Example

The Klang Gate monitoring network has been used as an example (Fig. 1). All computation for network adjustment and deformation detection has been solved by utilizing a computer package DEFORM99 (Ong, 1999) and DEFORM2 (Ranjit, 1999).

The monitoring network consists of two-epoch observation with 4 points. The first epoch consists of 17 uncorrelated observations (9 horizontal distance with standard error of 3 millimeters and 8 horizontal angles with 3 seconds of standard error). While, the second epoch consists 16 uncorrelated observations (8 horizontal distances with standard error of 3 millimeters and 8 horizontal angles with 3 seconds of standard error).

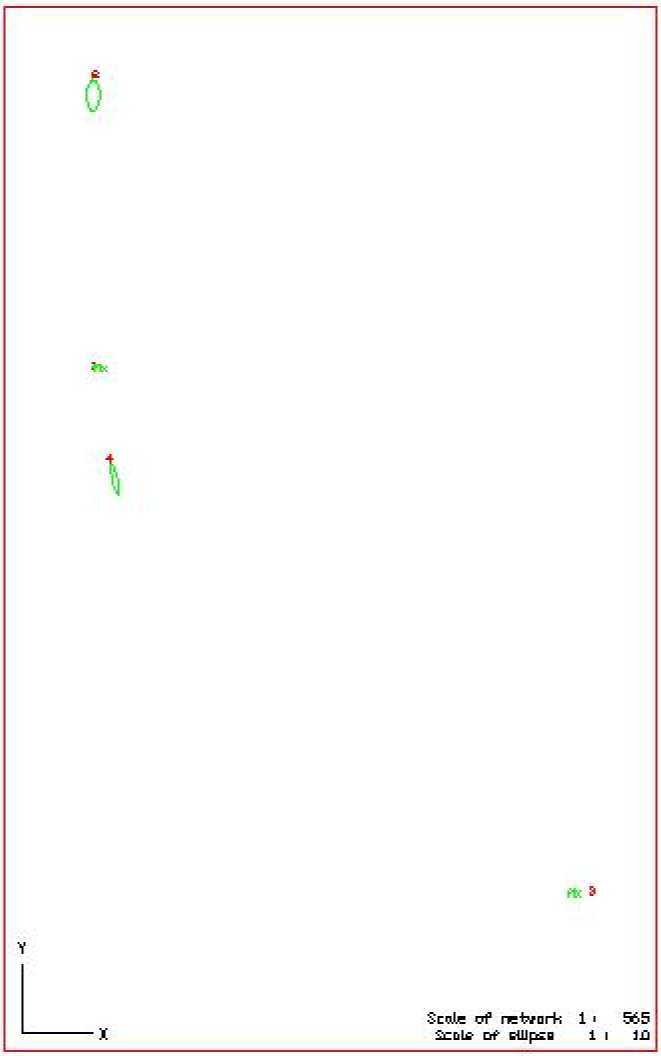

Figure 1: Monitoring Networks

Least square estimation of each epoch is carried out by fixing coordinates $x_{1,}y_1$ and x_2 (minimum constraint solution). The significance level for Chi-square and TAU test was chosen as 0.05. The criterion for convergence was set to 0.0001 meter. Both epochs converged at the second iteration. For first epoch, estimated variance factor were 1.169346, while second epoch is 1.659807. The least square estimation shown each epoch passed both global and local test.

The displacement vectors of the monitoring network are determined by using congruency test and IWST with free network datum definition (point 1, 2, 3 and 4). Significance level for deformation analysis was chosen as 0.05. The tolerance value were taken as 0.0001 meter. The variance test passed between 1.419 < 2.720 for both methods.

Global congruency test passed in range 0.486 < 2.636. The congruency test and IWST verified all point as stable. The result of displacement vector is tabulated in Table 1 below. The graphical interpretation is shown in Figure 2 and 3 for congruency test and IWST (displacement vector) respectively.

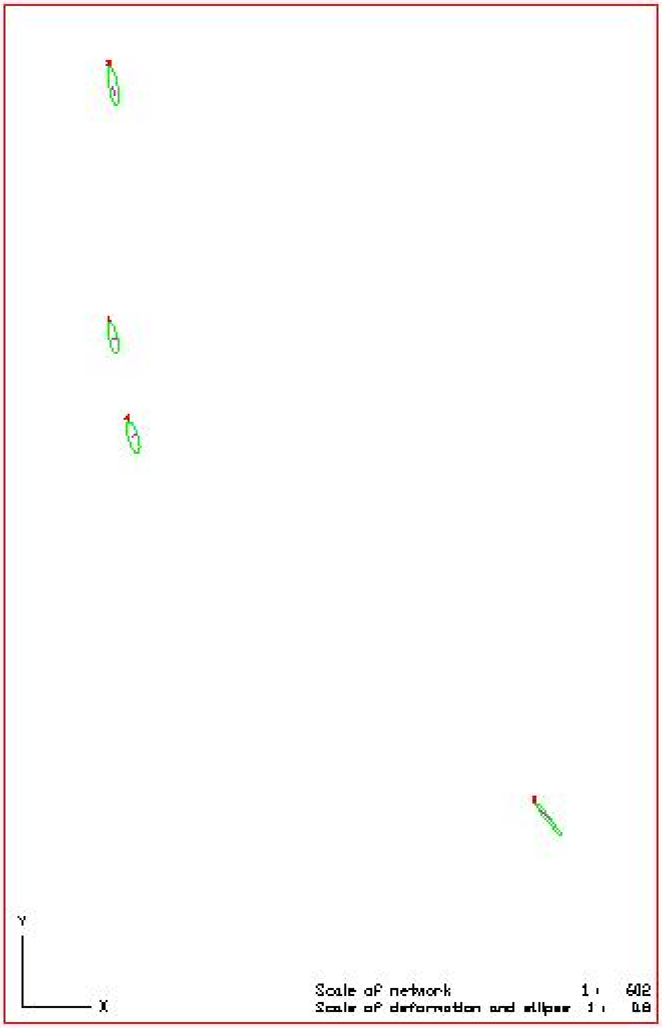

Figure 2: Congruency Testing

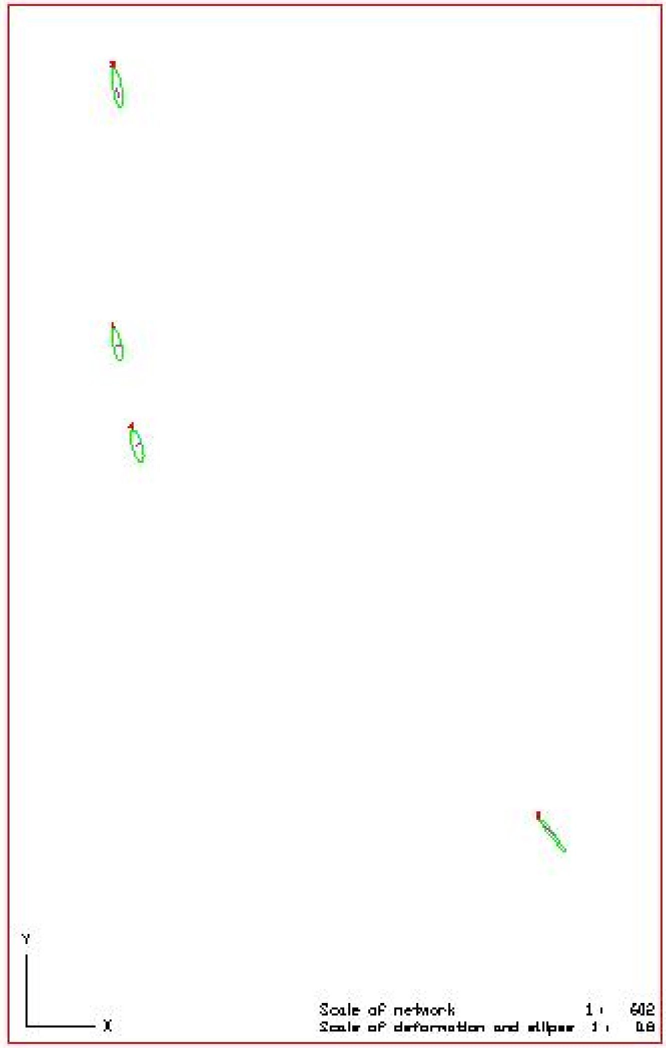

Figure 3: (IWST)

Network point	Congruency Test (m)	IWST (m)
1	0.0006	0.0002
2	0.0015	0.0015
3	0.0019	0.0023
4	0.0006	0.0003

Table 1: Displacement vector between congruency test and IWST

4.0 Conclusion

This paper has presented a detail procedure of deformation analysis, consisting of least square estimation, deformation detection and deformation modeling. During the analysis, rigorous method offers better interpretation for displacement and deformation model. In addition, geodetic method can help other colleagues such as civil engineer to understand the movement of the object from displacement vector.

5.0 Reference

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