GEOMETRIC ASPECTS EVALUATION OF GNSS CONTROL NETWORK FOR DEFORMATION MONITORING IN THE JATIGEDE DAM REGION

Made Ditha Ary Sanjaya1*, T. Aris Sunantyo2, and Nurrohmat Widjajanti3

1 Postgraduate Student at Geomatic Engineering, Engineering Faculty Universitas Gadjah Mada, Indonesia
2,3 Lecturer at Geodetic Engineering Department, Engineering Faculty Universitas Gadjah Mada, Indonesia
*E-mail: ditha.ary.sanjaya@gmail.com
Received: 2 February 2018; Revised: 14 March 2018; Approved: 6 December 2018

Abstract. Many factors led to dam construction failure so that deformation monitoring activities is needed in the area of the dam. Deformation monitoring is performed in order to detect a displacement at the control points of the dam. Jatigede Dam deformation monitoring system has been installed and started to operate, but there has been no evaluation of the geometry quality of control networks treated with IGS points for GNSS networks processing. Therefore, this study aims to evaluate the geometric quality of GNSS control networks on deformation monitoring of Jatigede Dam area. This research data includes the GNSS measurements of five CORS Jatigede Dam stations (R01, GG01, GCP04, GCP06, and GCP08) at day 233 with network configuration scenarios of 12 IGS points on two quadrants (jat1), three quadrants (jat2), and four quadrants (jat3 and jat4). GNSS networks processing was done by GAMIT to obtain baseline vectors, followed by network processing using parameter method of least squares adjustment. Networks processing with least squares adjustment aims to determine the most optimal by precision and reliability criterion. Results of this study indicate that network configuration with 12 IGS stations in the two quadrants provides the most accurate coordinates of CORS dam stations. Standard deviations value of CORS station given by jat1 configuration are in the range of 2.7 up to 4.1 cm in X-Z components, whereas standard deviations in the Y component are in the range 5.8 up to 6.9 cm. An optimization assessment based on network strength, precision, and reliability factors shows optimum configuration by jat1.

Keywords: Jatigede dam, control network, IGS, GNSS

1 INTRODUCTION

Jatigede Dam is built on Baribis Thrust which is an intensive and complex tectonic geological structure that causes the level of the dam vulnerability to movement and landslide is increasing (Zakaria, et al., 2011).

Based on the Center for Volcanology and Geological Hazard Mitigation in 2006, Baribis Fault is one of the active faults that potentially produce devastating earthquakes and is in the zone VII of Indonesia’s area earthquake prone (Zakaria, et al., 2011).

One of the efforts to maintain safety of dam construction is to monitor the geometric aspects of the dam...
Deformation monitoring is an effective method for analyzing deformation characteristics that occurred in the dam area, and also capable to provide warning systems when there are abnormal symptoms of dams (Cetin, et al., 2000).

Dam deformation monitoring is conducted by using integration of several interrelated disciplines. Geodetic science can contribute in position data recording techniques which used to create an integrated detection system and movement monitoring that occur to dam using permanently installed multi sensors in dam areas. Geodetic sensors implemented are Global Navigation Satellite System (GNSS) and Robotic Total Station (RTS) that work in accordance with their respective functions. Furthermore, the sensor’s measurement data are integrated into a system so it could be accessed for practical and scientific purposes (Sunantyo, et al., 2012).

According to Kuang (1991), one of the major aspects of deformation monitoring is geodetic observation network optimization. Optimal means that the control network condition have satisfied the precision quality standards. Control network optimization could be assessed by monitoring observational data of deformation and controlled by IGS point observation data in some IGS distribution scenarios in the quadrant (Nursetiyadi, 2015). Selection of GPS networks with a good strength of figure and satisfied the reliability criteria are required to achieve optimal position accuracy (Lestari and Yulaikhah, 2013). To obtain good GNSS network geometry, constraining to IGS active stations is needed (Panuntun, 2012; Artini, 2014; and Nursetiyadi, 2015). GNSS network processing is necessary to select an equally distributed IGS stations by data quality, data availability, and good network configuration to obtain precise and consistent station coordinate (Ma’ruf and Rahman, 2008).

Determination of the optimal network monitoring should be done before the installation of monitoring sensors deformation, but the assessment of network optimization remains to be done after the installation of the equipment. Quality assessment of GNSS network is necessary due to the importance of Jatigede Dam. An assessment of geometrical aspect qualities on Jatigede dam monitoring network was done by processing the observation data of GNSS stations and involving the observation data of IGS stations. The quality assessment of GNSS and IGS control network configuration scenarios were conducted by precision and reliability aspects of the network.

2 MATERIALS AND METHODOLOGY

2.1 Data and Tools

Data used in this study were GNSS measurements of five CORS Jatigede Dam stations (R01, GG01, GCP04, GCP06, and GCP08) at doy 233 with a network configuration scenario of 12 IGS points on two quadrants (jat1), three quadrants (jat2), and four quadrants (jat3 and jat4). Other data involved in this study is the observation of 18 IGS points for each configuration on 20 August 2016 (doy 233).

![Figure 2-1: Jatigede Dam GNSS control network.](image-url)
2.2 Methods
Evaluation of control network was carried out on the scenario of GNSS network configurations in the Jatigede Dam Area by involving IGS stations. GNSS networks were processed by the principle of least squares adjustment to obtain the coordinate values of CORS station coordinates, as well as variance-covariance of parameters and observations to compute the precision and reliability of network.

Figure 2-2: Research workflow.

Figure 2-2 shows that GNSS network processing initiated by IGS network establishment to four network configurations consists of 12 IGS points on each network. Network configuration was designed on horizontal projection plane with the division of the quadrant as in Figure 2-3.

Network configurations in Figure 2-3 are jat1, jat2, jat3, and jat4. Jat1 network was established based on IGS position in two quadrants at the north of dam area. Jat2 network was designed
based on IGS position in three quadrants. Jat3 and Jat4 networks was designed based on IGS position in four quadrants.

GNSS configuration networks was followed by quality checking of CORS station observation data with TEQC. TEQC has main functions to translate, edit, and check observation data quality. Data that has been checked with TEQC is prepared for data processing with GAMIT. GAMIT processed uses least squares adjustment to determine estimate position of GNSS station, orbit and rotation parameters, and phase ambiguity (Lestari, 2006). This process produced network baselines vectors and the quality parameter of postfit rms and fract.

Baseline vectors that has been generated from GAMIT processing were used in the least squares adjustment parameter method of the control network to obtain coordinate values and precision of each station in dam area. Least squares adjustment parameter method was used to determining information or measurements of the parameter from geodetic observation data. Processing with least squares adjustment was done by determining amount of measurements (baseline), amount of parameters, and weight of the measurements.

Least squares adjustment computation was initiated by determining amounts of measurement (baseline) and amount of parameters of Jat1, Jat2, Jat3, and Jat4. The amount of measurements generated from each configuration is 210 baselines ($\Delta X_1, \Delta Y_1, \Delta Z_1, \Delta X_2, \Delta Y_2, \Delta Z_2, \ldots, \Delta X_{70}, \Delta Y_{70}, \Delta Z_{70}$). Formation of weight matrix was performed based on the standard deviation value of the baseline measurement between the CORS dam control station and IGS points. The adjustment process yields the desired parameter value ("X" matrix), residual value (matrix "V"), corrected measurement value ("Lb" matrix).

Equation of measurement is computed by using mathematical relationship between parameter of measurement (approached coordinate) and observed value (baseline vector) such as (2-1) up to (2-3):

$$\Delta x_{ij} + v_i = X_j - X_i \quad (2-1)$$
$$\Delta y_{ij} + v_i = Y_j - Y_i \quad (2-2)$$
$$\Delta z_{ij} + v_i = Z_j - Z_i \quad (2-3)$$

$\Delta x_{ij}$, $\Delta y_{ij}$, and $\Delta z_{ij}$ are baseline vector of point i to j, $v_i$ are residual value, and $X_i$, $Y_i$, and $Z_i$ are coordinate values. The output is the coordinate value and precision of each control station in the dam area.

Quality of GNSS network configuration can be seen on 2D precision represented by absolute error ellipse. Absolute error ellipse computation was computed using standard deviation values of CORS coordinates using equations (2-4) and (2-5).

$$\sigma_{\text{max}}^2 = \frac{1}{4} \left[ \sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_z^2} \right] \quad (2-4)$$
$$\sigma_{\text{min}}^2 = \frac{1}{4} \left[ \sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_z^2} \right] \quad (2-5)$$

$\sigma_{\text{max}}$ is semi major axis, $\sigma_{\text{min}}$ is semi minor axis, and $\sigma_x^2$, $\sigma_y^2$ are variance of eigen value from variance-covariance of random vector matrix.

Network configurations quality also can be represented in network strength factor by considering the correlation between baseline vector component of GNSS network. Computation network strength factor in equation (2-6) was completed by the variance-covariance of parameters matrix that shows the influence of the configuration strength of network as deformation monitoring objective.

$$\text{Network strength factor} = \frac{\text{trace}(A^T C^{-1} A)^{-1}}{u} \quad (2-6)$$
Trace\( (A^T C^{-1} A)^{-1} \) is summation of diagonal components of \( (A^T C^{-1} A)^{-1} \) matrix, and \( n \) is amount of parameters.

GNSS network precision and reliability were computed based on variance-covariance matrix of coordinates that had been generated from least squares adjustment. Precision criterion is performed by analysis of scalar function optimization criteria of A-optimality, D-optimality, and E-optimality. Computation of GNSS network optimization criteria of precision and reliability is completed by scalar function optimization criteria of A-optimality, D-optimality, and E-optimality of eigen values for each configuration (Grafarend, 1974) are shown in equation (2-7) to (2-9).

\[
\text{A-optimality} \\
\text{trace} (\Sigma xx) = \lambda_1 + \lambda_2 + \ldots + \lambda_n = \min 
\]

\[
\text{D-optimality} \\
\text{Det} (\Sigma xx) = \lambda_1 \times \lambda_2 \times \ldots \times \lambda_n = \min
\]

\[
\text{E-optimality} \\
\lambda_{\text{maks}} = \min
\]

\( \lambda_1, \lambda_2, \ldots, \lambda_n \) are eigen value of matrix \( \Sigma xx \), and \( \lambda_{\text{maks}} \) are maximum eigen value from \( \Sigma xx \) matrix.

Network reliability analysis is completed by computations of individual redundancy value, internal reliability and external reliability. In accordance to Yalcinkaya and Teke (2006), the reliability of the control network is computed by equation (2-10) to (2-12).

\[
\text{Individual redundancy} \\
Z = r_j = (Q_{vv})_j P_j \quad (2-10)
\]

\( Q_{vv} \) is cofactor matrix of the residuals, \( P \) is weight matrix of the observations, and \( r_j \) is individual redundancy value.

\[
\text{Internal reliability} \\
Z = |\Delta_{0j}| = m_0 \sqrt{\frac{w_0}{p_{r_j}}} \quad (2-11)
\]

\( m_0 \) is standard deviation of unit weight, \( w_0 \) is lower bound for the non-centrality parameter in dependency of the significance level \( (\alpha) \) and the required minimum power of the test \( (1-\beta_0) \), and \( \Delta_{0j} \) is internal reliability criterion.

\[
\text{External reliability} \\
Z = \delta^2_{0j} = \frac{1-r_j}{r_j} w_0 \quad (2-12)
\]

\( \delta^2_{0j} \) is external reliability criterion.

3 RESULTS AND DISCUSSION
3.1 GAMIT Processing Result

GAMIT processing resulted based on quality parameters of the process. There are postfit nrms and fract values. Fract values are shown in Figure 3-1 and postfit nrms values are shown in Figure 3-2.

Figure 3-1: Visualization of fract values for each CORS stations.

Figure 3-1 shows fract values visualization for five stations in four IGS network configurations. Fract values were accepted if the value was less than 10. Figure 3-1 also explains variation of fract values were similar on each CORS. Jat3 and jat4 network configurations show relatively identical graph considering both networks were designed in four quadrants. Jat3 and jat4 configurations produce nearest value to zero in longitude and radius components of fract.
Table 3-1: Example of baseline vectors and their standard deviations.

<table>
<thead>
<tr>
<th>No.</th>
<th>Baseline</th>
<th>( \Delta X ) (m)</th>
<th>( \Delta Y ) (m)</th>
<th>( \Delta Z ) (m)</th>
<th>( \sigma \Delta X ) (cm)</th>
<th>( \sigma \Delta Y ) (cm)</th>
<th>( \sigma \Delta Z ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>GCP4 to GCP6</td>
<td>-87.62512</td>
<td>34.02835</td>
<td>349.32539</td>
<td>0.722</td>
<td>1.753</td>
<td>0.467</td>
</tr>
<tr>
<td>2.</td>
<td>GCP4 to GCP8</td>
<td>-1233.52942</td>
<td>-248.05762</td>
<td>790.88403</td>
<td>0.747</td>
<td>1.813</td>
<td>0.483</td>
</tr>
<tr>
<td>3.</td>
<td>GCP4 to GG01</td>
<td>-290.80514</td>
<td>-77.19233</td>
<td>-146.75211</td>
<td>0.787</td>
<td>1.848</td>
<td>0.484</td>
</tr>
<tr>
<td>4.</td>
<td>GCP4 to R01</td>
<td>-1069.1076</td>
<td>-345.08832</td>
<td>-395.18543</td>
<td>0.755</td>
<td>1.800</td>
<td>0.479</td>
</tr>
<tr>
<td>5.</td>
<td>GCP6 to GCP8</td>
<td>-1145.9043</td>
<td>-282.08597</td>
<td>441.55864</td>
<td>0.58</td>
<td>1.413</td>
<td>0.374</td>
</tr>
</tbody>
</table>

Fract values indicated the absence of gross error. Fract also indicated that apriori coordinate values were appropriate and given constraints were correct.

GAMIT processing resulted by baseline vector values between GNSS stations and their standard deviations. Generated baselines were used for least squares adjustment, whereas their standard deviations were used as weight of measurements. Some baseline vectors and their standard deviation values of each baseline were shown in Table 3-1. Table 3-1 shows the baseline vectors results of network processing by GAMIT and their standard deviations. Standard deviation value of baseline vectors is in fraction of millimeter up to a centimeter.

3.2 Least Squares Adjustment Result

Least squares adjustment computation generated CORS coordinates estimation and their standard deviations. Standard deviations of CORS coordinates are shown in Figure 3-3.
Based on standard deviations in Figure 3-3, jat1 is network with highest coordinate precision compared to network configurations with IGS positions in four quadrants (jat3 and jat4 configuration). Jat3 network shows widest range of standard deviations precision of 3.552 cm up to 11.86 cm, while jat1 network has the smallest standard deviation range of 2.681 cm up to 6.903 cm. The Y component on the graph has a relatively high standard deviation values. Highest standard deviation that shown in Y component shows lowest precision among other components. X and Z components on each CORS had high precision with standard deviation value below 8 cm in each configuration. Jat1 network shows highest coordinate precision compared to network configurations with IGS positions in four quadrants (jat3 and jat4).

3.3 Absolute Error Ellipse of GNSS Network Result

Error ellipse was computed to represent 2D precision of each network configurations. Error ellipse results are presented in Table 3-2. Table 3-2 shows position precision of point represented by $\sigma_{\text{min}}$ and $\sigma_{\text{max}}$ values on the X and Y axes on networks. Value of $\sigma_{\text{min}}$ and $\sigma_{\text{max}}$ ellipse error have precision in centimeter fraction. Based on Table 3-2, jat1 configuration was the network with smallest ellipse error among other configurations. Ellipse error values of each configurations are shown in centimeter fraction. Based on network purpose of detecting deformation in very small size, ellipse error values were still quite large. Network with a smaller ellipse error was needed as another strategy to obtain optimal deformation monitoring network.

3.4 Network Strength Factor Computation Result

Network strength factor is determined by the variance-covariance matrix. If the value of the network power factor is small, then the network is said to have good quality and vice-versa. The network strength factor results is shown in Table 3-3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Network Configuration</th>
<th>Network Strength Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>jat1</td>
<td>$1.29 \times 10^{-7}$</td>
</tr>
<tr>
<td>2.</td>
<td>jat2</td>
<td>$2.68 \times 10^{-7}$</td>
</tr>
<tr>
<td>3.</td>
<td>jat3</td>
<td>$1.50 \times 10^{-7}$</td>
</tr>
<tr>
<td>4.</td>
<td>jat4</td>
<td>$2.86 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Based on Table 3-3, it can be seen that configuration with IGS points in the four quadrants has a high dependence on the geometry of treated IGS network to CORS coordinates precision. Long distances between Dam GNSS control network and IGS locations are the factors that network geometry of IGS points in a particular quadrant determine the value of network strength factor. This makes jat1 configuration with IGS points in the two quadrants is the best configuration.
Jat1 configuration is the best network in terms of dependence on IGS geometry because of the minimum network strength factor value that is $1.29 \times 10^{-7}$.

### 3.5 Precision and Reliability of GNSS Network

Analysis results of scalar function optimization from criterion of precisions of A-optimality, D-optimality, and E-optimality. The minimum value on each computed precision criteria shows the best GNSS network quality among configurations. Values of network precision computation were shown in Table 3-4.

Table 3-4: Network configuration precision value.

<table>
<thead>
<tr>
<th>Precision Function</th>
<th>jat1</th>
<th>jat2</th>
<th>jat3</th>
<th>jat4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-optimality</td>
<td>$3.08 \times 10^{-2}$</td>
<td>$5.23 \times 10^{-2}$</td>
<td>$7.43 \times 10^{-2}$</td>
<td>$6.73 \times 10^{-2}$</td>
</tr>
<tr>
<td>D-optimality</td>
<td>$9.19 \times 10^{-4}$</td>
<td>$8.39 \times 10^{-4}$</td>
<td>$1.01 \times 10^{-4}$</td>
<td>$2.84 \times 10^{-4}$</td>
</tr>
<tr>
<td>E-optimality</td>
<td>$6.42 \times 10^{-1}$</td>
<td>$9.99 \times 10^{-1}$</td>
<td>$1.52 \times 10^{-1}$</td>
<td>$1.38 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Table 3-4 represents the optimization criteria of the network from homogeneity and isotropy aspect of the configuration. The minimum A-optimality value was in jat1 configuration with value of $3.08 \times 10^{-2}$, and maximum value was in jat3 configuration with value of $7.43 \times 10^{-2}$. The A-optimality value indicated the homogeneity of a configuration so that jat1 network was the best in terms of baseline homogeneity. The jat1 network has relatively long baselines compared to jat3 or jat4 networks that has heterogeneous baseline length although jat3 or jat4 were established with IGS points deployment on four quadrants. Minimum value of D-optimality was found in jat1 configuration with value of $9.19 \times 10^{-4}$, while the maximum value was in the jat3 configuration with a value of $1.01 \times 10^{-37}$. E-optimality criteria of jat1 configuration shows lowest value of $9.69 \times 10^{-3}$, whereas the jat3 configuration has the highest value of $1.52 \times 10^{-2}$. The minimum D-optimality value represents the isotropic configuration, that showed the network physical character in all directions.

Individual redundancy value indicated an unreliable measure of gross errors in network processing (Kuang, 1991). Individual redundancy value was derived from the diagonal element of residual cofactor matrix that has been generated by least squares adjustment. Individual redundancy for network baselines on average between the CORS on each configuration visualized in Figure 3-4.

Figure 3-4 shows individual redundancy values of network configuration. Network have satisfied the criterion of critical value that was greater than 0.4. Jat1 configuration has the highest average individual redundancy compared to jat2, jat3, and jat4 networks. Figure 3-4 shows that jat1 network was the most optimal network considering the individual redundancy aspect. This result implied that jat1 network has the best ability to detecting small gross errors in network processing.

Internal reliability of control network illustrates the quality that refers to the minimum limit of gross errors that can be detected on numerous observations for the given probability value of error (Kuang, 1991). Internal reliability has critical value of less than $6m_j$ that expressed by Marginally Detectable Error (MDE). Internal
reliability computation of GNSS network baselines visualized in Figure 3-5.

Figure 3-5: Average internal reliability value.

Figure 3-5, shows average values of networks internal reliability of each baseline components. Maximum reliability value is shown in Y (|ΔX|) component, while the minimum reliability value is shown in component Z (|ΔZ|). Configuration with maximum internal reliability value indicates low sensitivity to gross error. The maximum value of internal reliability shows less reliable observation, while the minimum reliability value indicates high sensitivity to gross errors. Visualization of internal reliability shows that most reliable network configuration is jat1 network.

External reliability of networks referred to results of individual redundancy computation. In this study, the expected external reliability value was above the critical value of less than 6. This value was expressed in Bias to Noise Ratio (BNR). Results of external reliability computation on GNSS network baselines are visualized in Figure 3-6.

Based on Figure 3-6, it can be seen the average value of external reliability of each baseline components on each GNSS networks. Computation of average external reliability on entire components shows that jat1 network produced the lowest average value compared to the configuration of jat2, jat3, and jat4. The graph shows that the jat1 network has the smallest effect that has been caused by the presence of an undetectable random error on GNSS observations in network processing.

4 CONCLUSION

GNSS network configurations with IGS positions in two quadrants (jat1) is the highest precision network based on estimated coordinates. Utilization of IGS stations in network processing was able to generate precision on X and Z components in the range of 2.7 up to 4.1 cm, while on the Y component the precision is in the range 5.8 up to 6.9 cm.

Optimization assessment of GNSS network configurations shows that Jatigede CORS network is precise and reliable for deformation monitoring by network processing with deployment of IGS station data in jat1 configuration. Cconfiguration of 12 IGS stations in two quadrants (jat1) produced the best network based on network strength, precision, and reliability. jat1 configuration is able to generate minimum value on network strength factor and external reliability while providing maximum value on individual redundancy values. This result shows that network processing of network that established by IGS stations deployment on two quadrants is more optimal than network processing of network that established by IGS stations deployment IGS stations deployment of three and four quadrants (jat3 and jat4).
ACKNOWLEDGEMENTS

The authors would like to "Satuan Kerja Non Vertikal Tertentu" of Jatigede Dam dan Leica Geosystems Indonesia for helping this research. The authors thank all the parties who helped provide advices and assistances during the implementation of research.

REFERENCES

Artini, SR. (2014), GNSS CORS GMU1 Stations Positioning with Global and Regional GPS Control Point Combinations, PILAR Jurnal Teknik Sipil, 10(1), Yogyakarta.
Ma’ruf, B., and Rahman, M. A., (2009), Analysis of Baseline-per-baseline Baseline Processing and Session-per-sessions Techniques on GPS Network Adjustment, National Seminar on Data Revitalization Yogyakarta.