Deformation detection for ISKANDARnet

M. C. Lim*,1, H. Setan1, R. Othman1 and A. K. Chong2

Tragedies and disasters in the past have shown the threats that are associated with large construction projects. A timely identification of precursory movements may save lives and minimise collateral damage. An advanced global positioning system (GPS) continuously operating reference station network known as ISKANDARnet is operated continuously to detect deformations in Iskandar, State of Johor, Malaysia. In this study, three GPS continuously operating reference stations from the ISKANDARnet were used as the object stations along four nearby international GNSS service stations (NTUS, XMIS, COCO and PIMO) used as reference stations. The GPS data were streamed and processed by a GPS processing software module, Bernese processing engine. A deformation analysis module was developed using the MATLAB programming language to carry out continuous two-epoch analyses. The development also involves the implementation of the iteratively weighted similarity transformation method and a final S-transformation to analyse the GPS data. By applying these techniques, unstable object points were identified within the monitoring network and accurate displacement vectors were computed. The time-based variation of the displacements was shown in this paper. Test results showed that the system performed satisfactorily.

Keywords: GPS, Continuously operating reference station, Deformation monitoring, Malaysia

Introduction

Disasters such as landslides and failures of man-made structures seldom occur without warning. Through a strategic monitoring of a deformable object, an abnormal behaviour can be detected and a warning can be issued quickly. Nevertheless, the acquisition of deformation parameters is one of the essential goals of deformation monitoring. A number of methodologies and techniques have been used for this purpose. In general, deformation measurements have the following features [2]:

(i) higher measurement accuracy requirement
(ii) repeatability of observations
(iii) integration of different types of observations
(iv) network may be incomplete, scattered in space and time
(v) complicated analysis of the acquired data.

To meet the specific needs of continuous deformation monitoring in Malaysia, a high accuracy and fast response system is urgently required to detect deformations constantly, so that equipment and personnel can be evacuated in advance of a structural failure, land subsidence or landslide. The objective of this paper is to validate the method of continuous deformation analysis, as well as provide a visual technique to continuously display the displacements on a computer screen.

Current deformation monitoring systems

As discussed in [1], global positioning system (GPS) sensors are able to provide fully automated and continuous sub-centimetre displacement detection in near real-time. Numerous applications of GPS for the purpose of deformation monitoring have been carried out. Four suitable and currently operating continuous deformation monitoring systems are presented as follows.

Continuously operating reference station (CORS) GPS network

Regional scale GPS networks have been used for deformation monitoring purposes for over a decade. A few examples include the Western Canada deformation array (WCDA), which is a permanent GPS tracker network established by the Geological Survey of Canada [14], the GPS earth observation network (GEONET) which is operated by the Geographical Survey Institute in Japan [15], the Southern California integrated GPS network (SCIGN) [10] and the South Pacific regional GPS network (SPRGN) [7]. These GPS networks operate continuously in automatic mode and use the regression analysis method as a prediction tool for the underlying relationships between absolute and relative variables in the identification of transient signals.

1Department of Geomatic Engineering, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
2Department of Surveying and Spatial Science, Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, Qld., Australia
*Corresponding author, email mengchanlim@yahoo.com

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GNSS/local positioning sensors (LPSs)/local sensors (LSs) based online control and alarm system (GOCA)

The GOCA is a multi-sensor system that may be set up as an early warning tool for natural hazards and deformations of man-made structures. It comprises two types of software components which are the GOCA hardware-control and communication module, and the GOCA deformation analysis module as indicated by [11]. The GOCA deformation-analysis software is responsible for the further processing of the GNSS and LPS data in a three-step sequential adjustment procedure. The first step initialises the monitoring reference frame which consists of stable reference points. The second and third steps comprise the geo-referencing of the three-dimensional (3D) object point coordinates in the reference frame and the simultaneous deformation analysis respectively. Both least squares and robust techniques (L1-norm and M-estimators) are applied. The deformation analysis step is an online displacement estimation integrating Kalman filtering for the estimation of the object point state vector of displacements, velocities and accelerations. With the aid of a finite-element model (FEM), common modelling can be extended by incorporating the results of geodetic displacement estimation with the results of Kalman filtering and the data from the physical observation of the local sensors to show the movement trend of the deformable area.

Real-time deformation monitoring system

The establishment of a real-time deformation monitoring system was presented in [21]. An adaptive Kalman filtering with a near real-time transmission of deformation results via a general packet radio service data modem was implemented, as well as the issue of an alarm via SMS when trigger levels were reached [22]. A benchmark test of the application software was carried out at Nanyang Technology University (NTU), Singapore. In this test, only real-time predicting and filtering were applied to the acquired data from a motorised total station and GPS. The filtered results were rigorously evaluated using an iterative weighted similarity transformation (IWST) technique [2] to minimise the effect of points with large displacements.

Deformation detection system (DDS)

The DDS is a software composed of a series of modules that automate surveying tasks, handle the database management and provide a graphical presentation of the results as described in [6]. The processed data are available for further analysis in near real-time. The DDS is capable of locating unstable reference stations using an IWST of the displacements [3]. An alarm is triggered when the displacements reach a predefined threshold. In summary, a fully automated and continuous deformation monitoring can be achieved by the DDS with multi-sensor systems.

ISKANDARnet

In the fast growing economic region of Southern Peninsular Malaysia (State of Johor), known as Iskandar, substantial activities are undertaken, particularly in relation to the construction and the provision of infrastructure (Fig. 1). These activities require a precise and reliable positioning service based on the global positioning system (GPS). Any deformation or subsidence at a site can be modelled by applying the network-based RTK (N-RTK) technique. The N-RTK is a carrier phase-based positioning technique that combines the measurements from multiple reference stations, and thus generates a ‘network correction’ which can be applied to longer baseline lengths. The implementation of N-RTK requires a network of permanent monitoring stations known as CORS, communication links for the data streaming of corrections and a processing centre (i.e. control centre).

In summary, GPS measurements are recorded at the CORSs and streamed to the control centre via internet links. Data gathered at the control centre are processed to model various GPS errors and to generate the N-RTK corrections. The School of Surveying & Spatial Information Systems, University of New South Wales (UNSW), Sydney, Australia, is collaborating with the Geodynamics (G&G) Research Group, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia (UTM), in the development of an N-RTK system which forms the continuous deformation detection system, known as ISKANDARnet.

The three CORSs (Fig. 2) established around the economic zone and within the regional international GNSS service (IGS) stations (NTUS, XMIS, COCO and PIMO), form the ISKANDARnet. The local stations

1 Location of the ISKANDARnet

2 Local ISKANDARnet points used as object stations

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are equipped with dual-frequency Trimble 4700 receivers, micro-centred L1/L2 antennas, server computers, internet connections and uninterrupted power supplies (UPS). All sites were investigated for multipath problems and structural stability.

**System development approach**

Slow and small deformations can be difficult to be continuously identified because they appear as a transient signal. However, with the help of the new GPS CORS network, namely the ISKANDARnet, it should be easier to detect these types of deformations. In this study, the three stations of the ISKANDARnet were used as object stations for detecting land deformations. The Singapore IGS station and the CORSs in the neighbouring countries were employed as reference stations. The GPS data were streamed via internet from the CORS in Radio Technical Commission for Maritime Service (RTCM) format. The RTCM was network transported via internet protocol (NTRIP). The GPS data processing and data handling were carried out by Bernese processing engine (BPE).

The deformation analysis was based on the current approach of deformation analysis. The IWST is becoming popular for geodetic deformation monitoring that employs GPS as monitoring devices [4]. Thus, the IWST method was applied to perform the deformation analysis to investigate the stability of each station of the ISKANDARnet. The principle of IWST is explained in detail later. An MATLAB-based deformation analysis software was developed in-house. It uses the IWST method to locate the unstable points within the monitoring network and produces time series graphs of the displacements in terms of northing, easting and height (up). By and large, the analysis methods demonstrated here were similar to the approach of the DDS [20]. Nevertheless, an innovative approach was implemented in the framework of the deformation detection system. There were five stages required to implement the continuous network deformation detection as shown in Fig. 3.

**Stage 1: GPS data streaming**

The GPS data were streamed continuously by using the BKG Ntrip Client Version 1.8, a GPS data streaming software developed by the Federal Agency for Cartography and Geodesy [8]. The ISKANDAR.net stations (ISK1, ISK2 and ISK3; iskandarnet.fksg.utm.my) and the IGS stations (BAKO, NTUS, PIMO and XMIS; www.igs-ip.net) provided real-time data streaming services. These stations formed a network containing seven CORSs.

**Stage 2: data preparation for the deformation detection module**

At this stage, the popular GPS processing software Bernese v. 5-0 was used for the GPS data processing. The Bernese software is commonly used to process GPS data for deformation monitoring [9], [12], [13], [23]. By implementing the Bernese software, the data screening, cycle slip detection, ambiguity resolution and network adjustment of the GPS data did meet the desired criteria. Subsequently, degree of freedom, a posteriori variance factor, variance-covariance matrix, approximate coordinates and estimated coordinates (in geocentric Cartesian coordinates) could be obtained. These parameters were required for a two-epoch deformation analysis. Consequently, these parameters were input for the deformation detection module (stage 3).

**Stage 3: deformation detection module**

The deformation detection module was developed using the MATLAB software. This module determines the stability of every monitoring station by computing the 3D displacements which are then used to evaluate whether the points have moved. The deformation analysis technique implemented in the in-house software is a continuous two-epoch (i.e. any epoch against initial epoch) analysis using the IWST method. The IWST method belongs to the family of ‘robust’ methods. It enables the determination of the best datum, in a sense that it has the minimal distorting influence on the vector of displacements [16]. A flow chart of the IWST method is illustrated in Fig. 4. It shows the overall procedure of the deformation analysis of one-dimensional (1D), two-dimensional (2D) and 3D point detection using the IWST and a final S-transformation analysis. It also highlights that the final S-transformation is significant at the final step of analysis as discussed in the next paragraph.

**Formation of matrix G for the final S-transformation**

G is a configuration matrix for the datum defect, called inner constraint matrix. Basically, the matrix G depends on the type of network: 1D, 2D or 3D. For 1D, 2D and 3D networks, G is having maximum dimensions of
\( G^T = (1 1 1 1 \ldots 1_m) \) \hspace{1cm} (1)

For 2D surveying networks, the first two rows of the matrix \( G \) represent the translations in the \( x \) and \( y \) directions (\( t_x \) and \( t_y \)), the third row defines the rotation about the \( z \) axis (\( r_z \)) and the last row is the scale of the network. Equation (2) shows the components of the matrix \( G \) for a 2D network [18].

\[
G^T = \begin{pmatrix} 1 & 0 & 1 & \cdots & 1 & 0 \\ 0 & 1 & 0 & \cdots & 0 & 1 \\ y_1 - x_1 & y_2 - x_2 & \cdots & y_m - x_m \\ x_1 & y_1 & x_2 & \cdots & x_m & y_m \end{pmatrix} \] 

Equation (3) shows the components of the matrix \( G \) for a 3D network

\[
G^T = \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 & \cdots & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & \cdots & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & \cdots & 0 & 0 & 1 \\ 0 & z_1 & -y_1 & 0 & z_2 & -y_2 & \cdots & 0 & z_m & -y_m \\ -z_1 & 0 & x_1 & -z_2 & 0 & x_2 & \cdots & -z_m & 0 & x_m \\ y_1 & -x_1 & 0 & y_2 & -x_2 & 0 & \cdots & y_m & -x_m & 0 \\ x_1 & y_1 & z_1 & x_2 & y_2 & z_2 & \cdots & x_m & y_m & z_m \end{pmatrix} \] 

However, the size of the matrix \( G \) usually depends on the datum defect. Those datum elements that are not involved in the datum defect are removed from the matrix \( G \). For instance, if a 3D GPS network is utilised for deformation monitoring, the datum elements involved are \( t_x \), \( t_y \) and \( t_z \) only. Hence, the matrix \( G \) will be

\[
G^T = \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 & \cdots & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & \cdots & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & \cdots & 0 & 0 & 1 \\ 0 & z_1 & -y_1 & 0 & z_2 & -y_2 & \cdots & 0 & z_m & -y_m \\ -z_1 & 0 & x_1 & -z_2 & 0 & x_2 & \cdots & -z_m & 0 & x_m \\ y_1 & -x_1 & 0 & y_2 & -x_2 & 0 & \cdots & y_m & -x_m & 0 \\ x_1 & y_1 & z_1 & x_2 & y_2 & z_2 & \cdots & x_m & y_m & z_m \end{pmatrix} \] 

The coordinates used for the computation of the matrix \( G \) are reduced to the centroid or the centre of gravity of
the network [18] to simplify the calculations
\[
\begin{align*}
x &= x_i - \frac{\sum x_m}{m} \quad \text{(5a)} \\
y &= y_i - \frac{\sum y_m}{m} \quad \text{(5b)}
\end{align*}
\]
where \(x_i\) and \(y_i\) are provisional coordinates for point \(i\), \(m\) is the number of stations in monitoring network, \(\Sigma x_m\) is the sum of the \(x\) coordinates for all stations in the monitoring network and \(\Sigma y_m\) is the sum of the \(y\) coordinates for all stations in the monitoring network.

**Identification of unstable points using IWST**

The discussion is based on a two-epoch (initial epoch or epoch \(i\) against epoch \(j\) in a network adjustment. During the least squares estimation (LSE), the estimated coordinates of the epochs \(i\) and \(j\) (\(x_i\) and \(x_j\)) and their cofactor matrices (and) are computed and must pass the global test (chi-square) and the local test (Baarda method). Then it is possible to carry out the deformation analysis. Next, when comparing the two epochs of surveyed points, the vectors of displacements \(d\) and \(Q_d\), its cofactor matrix is calculated as shown in [18]
\[
\begin{align*}
d &= x_j - x_i \\
Q_d &= Q_x + Q_y
\end{align*}
\]
\(x_i\) and \(x_j\) must be in the same datum. If not, an S-transformation must be conducted before the calculation of \(d\) (Fig. 4).

At the beginning of the deformation analysis, the first matrix which must be computed is the weight matrix \(W\). For the first iteration \(k=1\), the matrix \(W\) is equal to \(I\) (i.e. \(W=I\)), where all the diagonal elements are 1 and all other elements are 0. In the second \((k+1)\) and all subsequent iterations, the diagonal elements of the weight matrix are defined as
\[
W^{(k+1)}(i, i) = \text{diag}[1/d^{(k)}]
\]
For 1D networks, there are some differences for the calculation of \(d^*\) and \(Q_d^*\). First, the displacements \(d\) are arranged in increasing order. The median is assigned unit weight 1 and zero weight is assigned to the other displacements \(d\). If the total number of \(d\) is an even number, the two middle (median) displacements \(d\) are assigned unit weight 1 and zero weight is assigned to the other displacements \(d\) [3]. Then, the new vector of displacements \(d^*\) and its cofactor matrix \(Q_d^*\) are [3]
\[
\begin{align*}
d^* &= \min \{ \sum [d_i - t_i] \} \\
Q_d^* &= S_{Q_d}S_d^\top
\end{align*}
\]
where \(t_i\) is the mean value of the middle displacements and \(d_i\) is the displacement of point \(i\).
\[
S = I - Gd^\top W G^{-1} G^\top W
\]
For a 2D network, the \(w\) elements of the weight matrix \(W\) are computed as follow
\[
\begin{align*}
w^{(k+1)}(1, 1) &= \frac{1}{d^{(k)}_x} \\
w^{(k+1)}(2, 2) &= \frac{1}{d^{(k)}_y} \\
w^{(k+1)}(1, 1) &= \frac{1}{d^{(k)}_x} \\
w^{(k+1)}(2, 2) &= \frac{1}{d^{(k)}_y} \\
w^{(k+1)}(2m - 1, 2m - 1) &= \frac{1}{d^{(k)}_{ym}}
\end{align*}
\]
where \(k\) is the iteration number.

For a 3D network, the \(w\) elements of the weight matrix \(W\) are computed as follow
\[
\begin{align*}
w^{(k+1)}(1, 1) &= \frac{1}{d^{(k)}_x} \\
w^{(k+1)}(2, 2) &= \frac{1}{d^{(k)}_y} \\
w^{(k+1)}(3, 3) &= \frac{1}{d^{(k)}_z} \\
w^{(k+1)}(3m - 2, 3m - 2) &= \frac{1}{d^{(k)}_{ym}} \\
w^{(k+1)}(3m - 1, 3m - 1) &= \frac{1}{d^{(k)}_{ym}} \\
w^{(k+1)}(3m, 3m) &= \frac{1}{d^{(k)}_{ym}}
\end{align*}
\]
It is possible that some \(d^{(k)}\) may approach zero during the iterations, causing numerical instabilities, because \(w^{(k)}\) becomes very large. There are two ways to solve this problem [3]:

(i) setting a lower bound (e.g. 0-0001 m). If \(d^{(k)}\) is smaller than the lower bound value, its weight is set to zero
(ii) replacing the weight matrix as \(w^{(k)} = 1/[d^{(k)} + \delta]\), where \(\delta\) is a tolerance value.

After that, \(d^{(k+1)}\) is computed using the following equations [3]
\[
\begin{align*}
d^{(k+1)} &= S_{Q_d^{(k+1)}}[d^{(k)}] \\
G = G^{(k+1)} - G^{(k)} = [d^{(k)} + \delta]
\end{align*}
\]
The \(G\) matrix is an inner constraint matrix. The dimensions of the \(G\) matrix are different for 1D, 2D and 3D networks. This concept was discussed previously in the paper. The iterative procedure continues until the absolute differences between the successive transformed displacements \(d\) are smaller than a tolerance value \(\delta\), 0-0001 m [3]
\[
|d^{(k+1)} - d^{(k)}| < \delta
\]
vector by using stable reference points (as verified by the previous IWST analysis) as datum. Consequently, elements of weight matrix $W$ are assigned 1 for stable reference points and 0 for other points to achieve the final $S$-transformation. Hence, the principle of congruency testing \[18\] is used for calculating the actual deformation displacement vector. In the final iteration, the displacement vector $d(F)$ and the final cofactor matrix $Q(F)$ of displacement vector are computed as

$$d(F) = S(F)d^{(k+1)}$$

(16)

$$Q_d(F) = S(F)Q_d S(F)^T$$

(17)

where $S(F) = I - G[G^T W(F)G]^{-1}G^T$ and $W(F) = I$ for stable reference points and 0 for other points based on the indication of statistical testing in equation (18).

When the vectors of the displacements and the variance-covariance matrix of each point are computed, the stability information of each point can be determined through a single point test. The displacement values and the variance-covariance matrix are compared with a critical value. Assuming that the point $i$ is tested, then, the algorithms are as follows [3], [16], [18]

$$T_i = \frac{d_i^T Q_d^{-1} d_i}{m\sigma_o^2} \sim F(m, df, \alpha)$$

(18a)

where $d_i$ is the displacement vector of point $i$, $Q_d$ is the variance-covariance matrix of point $i$, $m$ is the dimension of the confidence region (1, 2 or 3), $df$ is the sum of degrees of freedom of epochs $i$ and $j$, $\alpha$ is the significance level (usually chosen as 0.05) and $\sigma_o^2$ is the pooled variance factor

$$\sigma_o^2 = \frac{df_i \sigma_i^2 + df_j \sigma_j^2}{df_i + df_j}$$

(18b)

where $\sigma_i^2$ and $\sigma_j^2$ are a posteriori variance factors of epoch $i$ and epoch $j$, and $df_i$ and $df_j$ are the degrees of freedom of epoch $i$ and epoch $j$.

If the above test passes [i.e. $T_i \leq F(m, df, \alpha)$], then the point is assumed to be stable at a significance level $\alpha$. Otherwise, if the test fails [i.e. $T_i > F(m, df, \alpha)$], then the point is assumed to have moved.

**MATLAB-based in-house software description**

Figure 5 shows the block diagram and demonstrates the functionality of the in-house deformation analysis software.

**Choice of parameters**

A deformation analysis requires parameters such as provisional coordinates, estimated coordinates and a variance-covariance matrix. These parameters were provided by the Bernese, GPS processing software. The MATLAB-based in-house software searched and read the required parameters from the Bernese output file and applied them as input parameters to the deformation analysis. The program was designed to search the specified parameter according to the string name in the output file.

**IWST processing engine**

The core of the deformation analysis program is based on the principle of the IWST method. However, an initial checking of data and a test of the variance ratio were essential to ensure that common points, the same approximate coordinates and the same points names were used.
in the two epochs [18]. Thus, a statistical test named the variance ratio test was carried out to determine the compatible weighting between the two epochs. Because the IWST method required an iterative change in the weight matrix \( W \), loop commands were used to allow the iterative procedure to continue until a predefined condition was fulfilled. MATLAB commands such as for and while were used to formulate the loops (Fig. 4).

**Displacement detection**

The in-house software utilised a single point test for the detection of displacements and rejected any point if its displacement extended beyond the confidence region [16]. A detected point is flagged as unstable if a given point fails the test at the specified confidence level. At the final stage of processing, a deformation file is produced. It contains the summary of the data used, a statistical summary and station information such as whether a station was flagged as having moved or not.

**Stage 4: deformation visualisation module**

The trend analysis of the monitoring network is displayed by plotting the displacements of all the points against their error ellipses to visualise the stability of each station plus the trend of the movement. A software module embedded in MATLAB, Simulink, was capable of an interactive simulation. The deformations could be visualised continuously with a block diagram model which consisted of a set of equations as depicted in graphic form in Fig. 6.

The trend analysis of the monitoring network could be viewed and was updated at a fix time interval. The variation in the displacements could be visualised on-screen in separate graphs for northing, easting and height that were proportional to the associated time series results. Displacement vectors triggered an alarm when they exceeded a predetermined threshold.

**Stage 5: assessment and analysis**

This was the final stage in the development of the new approach. Both published (validated) data and field data were used in the assessment of the approach. The assessment was carried out for three aspects: data communication between Bernese and MATLAB softwares, analysis of the detected displacements and visualisation of deformations in a continuous mode. Further discussions are provided in the following sections.

**Testing of the S-transformation technique**

A program was developed to facilitate the detection of unstable points and the trend analysis of the changes in the coordinates of the geodetic network. As discussed previously, the program uses statistical testing methods such as the variance ratio test, IWST and a single point test. Three sets of published data were selected to test the program/software capability.

**Experimental dataset 1: 1D vertical reference network**

Figure 7 presents a vertical reference network with two survey campaigns, where point A was fixed [3].

The network adjustment was performed using an LSE. Then, the output of the LSE was used to compute the displacement vector \( d \) and its cofactor matrix \( Q_d \).

\[
d = \hat{X}_2 - \hat{X}_1 = \begin{pmatrix} A_{0.00} & B_{1.94} & C_{2.06} & D_{1.74} \end{pmatrix}^T \tag{19}
\]

\[
Q_d = Q_{b_2} + Q_{b_1} = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0.74 & 0.40 & 0.45 \\
0 & 0.40 & 0.60 & 0.40 \\
0 & 0.45 & 0.40 & 0.74
\end{pmatrix} \tag{20}
\]

Next, the displacements were arranged in increasing order (0-00, 1-74, 1-94, 2-06). Thus, points D and B (second and third displacements) were assigned unit weight (1) and points A and C (first and last displacements)

<table>
<thead>
<tr>
<th>Station</th>
<th>Single point test</th>
<th>Displacement vector/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stable</td>
<td>1-70</td>
</tr>
<tr>
<td>2</td>
<td>Stable</td>
<td>1-00</td>
</tr>
<tr>
<td>3</td>
<td>Stable</td>
<td>1-90</td>
</tr>
<tr>
<td>4</td>
<td>Moved</td>
<td>56-0</td>
</tr>
<tr>
<td>5</td>
<td>Moved</td>
<td>50-6</td>
</tr>
<tr>
<td>6</td>
<td>Stable</td>
<td>0-60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Single point test</th>
<th>Displacement vector/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stable</td>
<td>1-20</td>
</tr>
<tr>
<td>2</td>
<td>Stable</td>
<td>1-70</td>
</tr>
<tr>
<td>3</td>
<td>Stable</td>
<td>1-10</td>
</tr>
<tr>
<td>4</td>
<td>Moved</td>
<td>56-1</td>
</tr>
<tr>
<td>5</td>
<td>Moved</td>
<td>50-3</td>
</tr>
<tr>
<td>6</td>
<td>Stable</td>
<td>1-30</td>
</tr>
</tbody>
</table>
‘zero’ weight. (The translation parameter \( t_z \) in equation (9) is taken as the mean of two middle displacement, \( t_z = 1.84 \)). After the weighted similarity transformation (equation (13)) with the in-house software, the new vector of displacements \( \mathbf{d}' \) and its cofactor \( \mathbf{Q}_d' \) were as follows

\[
\mathbf{d}' = \mathbf{Sd} = (-1.84 0.10 0.22 -0.10)
\]

\[
\mathbf{Q}_d' = \mathbf{S}
\mathbf{Q}_d
\mathbf{S}^T
\]

Because the network was 1D, a direct formulation of the weight matrix was applied. The identification of unstable points clearly showed that only station A was unstable. Table 1 shows the results of the deformation analysis for the selected 1D levelling network.

Table 1 shows the displacements \( \Delta Z \) in the \( z \) direction when the points B and D are assigned unit weight. Another approach is to assign the unit weight based on the given stability information. Table 2 shows the results of the later approach. A comparison between Tables 1 and 2 demonstrates that more accurate displacement vectors can be obtained by assigning unit weights based on the stability information. The true value of the displacement of station A was 1.95 mm [3]. There was no significant displacement shown for the rest of the stations.

Experimental dataset 2: 2D monitoring network

The second dataset was a 2D simulated deformation network that consisted of six stations [19]. Epoch 1 consisted of 20 horizontal distance and 16 horizontal angle measurements. Epoch 2 contained 20 horizontal distance and 11 horizontal angle measurements. Three coordinates \((x_1, x_4, y_4)\) were fixed as initial datum. This network has simulated displacements at Stations 4 and 5 at epoch 2. Stations 4 and 5 featured displacements of 5 cm in \( x \) direction and 5 cm in \( y \) direction respectively.

By implementing the IWST for a 2D network, different components of the inner constraint matrix \( \mathbf{G} \) were adopted. Owing to only three datum defects for
Table 9 Stability analysis of the four reference stations using IWST

<table>
<thead>
<tr>
<th>Station</th>
<th>(D_x/m)</th>
<th>(D_y/m)</th>
<th>(D_z/m)</th>
<th>3D displacement vector/m</th>
<th>Test statistic versus critical value</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCO</td>
<td>0.0052</td>
<td>-0.0033</td>
<td>-0.0029</td>
<td>0.0068</td>
<td>0.000004 &lt; 8.742</td>
<td>Stable</td>
</tr>
<tr>
<td>ISK1</td>
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<td>-0.0067</td>
<td>-0.0050</td>
<td>0.0089</td>
<td>0.000009 &lt; 8.742</td>
<td>Stable</td>
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<td>0.000008 &lt; 8.742</td>
<td>Stable</td>
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<tr>
<td>NTUS</td>
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<td>-0.0058</td>
<td>0.0010</td>
<td>0.0080</td>
<td>0.000004 &lt; 8.742</td>
<td>Stable</td>
</tr>
<tr>
<td>PIMO</td>
<td>-0.0071</td>
<td>0.0024</td>
<td>0.0022</td>
<td>0.0078</td>
<td>0.00001 &lt; 8.742</td>
<td>Stable</td>
</tr>
<tr>
<td>XMIS</td>
<td>-0.0034</td>
<td>0.0067</td>
<td>-0.0004</td>
<td>0.0076</td>
<td>0.000002 &lt; 8.742</td>
<td>Stable</td>
</tr>
</tbody>
</table>

Table 10 Stability of all monitoring stations using a final S-transformation based on four stable reference points

<table>
<thead>
<tr>
<th>Station</th>
<th>(D_x/m)</th>
<th>(D_y/m)</th>
<th>(D_z/m)</th>
<th>3D displacement vector/m</th>
<th>Test statistic versus critical value</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCO</td>
<td>0.0052</td>
<td>-0.0033</td>
<td>-0.0029</td>
<td>0.0068</td>
<td>0.000004 &lt; 8.742</td>
<td>Stable</td>
</tr>
<tr>
<td>ISK1</td>
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<td>0.0076</td>
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<td>Stable</td>
</tr>
</tbody>
</table>

this 2D network, the dimensions of the matrix \(G\) were \(2m \times 3\), where \(m\) represents the number of stations [19]. Using the in-house software (based on IWST), stability information was produced as shown in Table 3. The published results [19] of the 2D network using congruency testing are shown in Table 4.

The displacement vectors of Tables 3 and 4 differ by a small amount. To achieve the same results as Table 4, a final S-transformation must be applied to the Table 3 results. In the final S-transformation, unit weights were assigned to the stable points (based on the stability information from the single point test) which were selected as the new datum. Then, the displacement vector and its cofactor matrix were computed. Table 5 shows the deformation analysis with the newly assigned weights. The results are now the same as those of Table 4. Figure 8 shows the simulated deformation monitoring network.

Comparisons between the three sets of results were conducted to identify differences in the estimated displacements. There are no differences between the final S-transformation and the confirmed result of the congruency testing [19]. Thus, a final S-transformation was implemented in the in-house deformation analysis software as a last step of the computations with the IWST method.

Experimental dataset 3: 3D GPS network

Two epochs of data of an established GPS network (in geocentric Cartesian coordinate system) [5] with seven stations were used to test the feasibility of the developed program. All baseline vectors exceeded 10 km. Epoch 1 consisted of 21 baseline vectors and epoch 2 of 17 baseline vectors.

As the datum defect of 3D GPS networks in an earth-centred Cartesian coordinate system is only 3, the dimension of the matrix \(G\) was \(3m \times 3\), where \(m\) is number of stations. The iteratively weighted transformations continued until the displacement vectors converged to a predefined limit. Table 6 shows the results of our deformation analysis of the two-epoch GPS data and Table 7 shows the published deformation analysis results [5] using congruency testing. Based on the published results, Stations 2 and 4 were unstable and the rest of the stations were stable. The MATLAB in-house deformation analysis software produced similar trends to those of the published results [5]. A comparison between Tables 7 and 8 shows that the deformation analysis result obtained with the IWST method was correct when a final S-transformation was applied. Figure 9 shows the graphical presentation of 3D GPS network by using Matlab.

Test results using ISKANDARNet data

There were seven stations in the deformation monitoring network. Four IGS stations were used as reference points: COCO, NTUS, PIMO, XMIS (Fig. 1) and three stations from the local ISKANDARNet (ISK1, ISK2 and ISK3) were used as test object points (Fig. 2). However, ISK2 was excluded as it was still under performance evaluation testing. The GPS data processing and the two-epoch deformation analysis were performed using two epochs of data (7 and 8 April 2010). After the GPS data processing with the Bernese software, two-epoch deformation analyses (at 5% significance level) were performed in two stages: stability analysis of reference stations using IWST and deformation analysis of all stations. The stability of the reference stations was vital in order to select a set of stable reference stations to perform the analysis for all stations in the monitoring network. The results of the stability analysis in Table 9 confirmed that all four reference stations were stable.

Subsequently, a deformation analysis of all six stations was carried out through a final S-transformation based on the stable reference points (Table 9). All six stations were verified as stable (Table 10). The results obtained illustrate that millimetre level displacements of GPS CORS stations can be detected. However, there was no significant movement shown as the displacements did not exceed the threshold.

Concluding remarks

The basis of deformation analysis of structural deformation and land subsidence monitoring for an economic zone in Southern Peninsular Malaysia was discussed in this paper. By and large, the idea of continuous two-epoch deformation analysis is aimed at providing daily solution. The deformation analysis is able to generate the results in numerical and graphical form once the 24 h GPS data (one epoch) were processed by the Bernese software. The total time taken for any epoch against initial epoch to complete GPS processing plus deformation analysis is around 15–20 min.
In addition, the MATLAB in-house deformation analysis software proved to have potential for providing high-quality stability information of the ISKANDARnet. Moreover, the final S-transformation computation has proved to be significant as the final step of computing the actual deformation displacement vector, subsequent to the IWST analysis. The experimental results based on the developed IWST and final S-transformation approaches were comparable with published results of the same datasets, thus confirming the suitability of the developed approach for this highly significant monitoring network. Future work will involve making the software fully automated.

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References