DEFORMATION MONITORING PROCEDURE AND SOFTWARE SYSTEM USING ROBUST METHOD AND SIMILARITY TRANSFORMATION FOR ISKANDARnet

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To my beloved mother and father

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ABSTRACT

Recently, repeated earthquake such as Sumatra earthquake (June 05 2012), Taitung earthquake (June 06 2012) and Honshu earthquake (June 08 2012) have brought the disastrous impacts on their nation and neighbourhood. Due to the geographical location of Malaysia proximity to Indonesia, only people in high rise buildings feel the tremors. However, with increased seismic activity in the region following a series of major earthquakes in recent years, deformation monitoring is desperately needed to monitor the physical facilities such as dams, bridges, Light Rail Transit (LRT), monorail networks and other major structures. A reliable deformation monitoring procedure and system has to be developed to ensure the displacements of structures are within the safety threshold. Among the available technologies, Global Positioning System (GPS) is increasingly being used for deformation monitoring. GPS sensors are able to provide fully-automated and continuous sub-centimetre displacement detection in real time. Therefore, a newly established GPS Continuous Operating Reference Station (CORS) network called ISKANDARnet was utilised to detect deformation displacement in Iskandar, Johor, Malaysia. In this study, three GPS CORS from ISKANDARnet had been utilised as the object monitoring stations along with four nearby International GNSS Services (IGS) stations (i.e.: NTUS (Singapore), XMIS (Christmas Island, Australia), COCO (Keeling Island, Australia) and PIMO (Quezon City, Philippines)) as the reference monitoring stations. GPS data was downloaded from File Transfer Protocol (FTP) server and processed by the high precision GPS processing software module, called Bernese Processing Engine (BPE). Subsequently, a continuous deformation analysis software system named ConDAS was developed using Matrix Laboratory (MATLAB) programming language to conduct a continuous two-epoch deformation analysis. By implementing the Iteratively Weighted Similarity Transformation (IWST) and final S-Transformation method, ConDAS is able to determine the measured displacement vector is statistically significant. The unstable object stations were identified and the displacement vectors were computed. The fluctuation of deformation displacement was visualised on-screen proportional to the associated time series results. The results obtained from deformation analysis of ISKANDARnet shows no significant displacement and all stations are stable within the threshold over these two years since 2010. Through the research, a robust deformation monitoring procedure and software system was attained which contributes to the current regional deformation studies in Malaysia.

ABSTRAK

Kebelakangan ini, gempa bumi yang berulang seperti gempa bumi Sumatra (05 Jun 2012), gempa bumi Taitung (06 Jun 2012) dan gempa bumi Honshu (08 Jun 2012) telah membawa impak dahsyat kepada negara dan jirannya. Oleh kerana kedudukan geografi Malaysia berdekatan dengan Indonesia, hanya penduduk di bangunan tinggi sahaja yang merasa gegaran. Walau bagaimanapun, dengan peningkatan aktiviti seismik di rantau ini berikutan beberapa siri gempa bumi utama dalam tahun-tahun kebelakangan ini, pemantauan deformasi amat diperlukan untuk memantau kemudahan fizikal seperti empangan, jambatan, Transit Aliran Ringan (LRT), rangkaian monorel dan lain-lain struktur utama. Suatu procedur dan sistem pemantauan deformasi yang boleh dipercayai perlu ditubuhkan untuk memastikan anjakan struktur berada dalam ambang keselamatan. Antara teknologi yang boleh didapati, Sistem Penentududukan Sejagat (GPS) telah banyak digunakan untuk pemantauan deformasi. Penderia GPS dapat mengesan pergerakan sub-sentimeter secara automasi dan berterusan dalam masa hakiki. Maka, suatu jaringan Stesen Rujukan yang Beroperasi Secara Terus (CORS) GPS yang baru ditubuhkan bernama ISKANDARnet telah digunakan untuk mengesan pergerakan deformasi di wilayah Iskandar, Johor, Malaysia. Dalam kajian ini, tiga stesen GPS CORS dari ISKANDARnet telah digunakan sebagai stesen pemantauan objek bersama dengan empat stesen International GNSS Services (IGS) yang berdekatan (iaitu NTUS (Singapore), XMIS (Christmas Island, Australia), COCO (Keeling Island, Australia) dan PIMO (Quezon City, Philippines)) sebagai stesen-stesen kawalan. Data GPS telah dimuat turun dari unit pemprosesan Protokol Pemindahan File (FTP) dan diproses oleh perisian pemprosesan GPS yang berkejituan tinggi bernama Bernese Processing Engine (BPE). Seterusnya, satu sistem perisian analisis deformasi bernama ConDAS telah dibangunkan dengan bahasa pengaturcaraan Matrix Laboratory (MATLAB) untuk melakukan analisis deformasi dua epok secara berterusan. Dengan melaksanakan Lelaran Transformasi Persamaan Berwajaran (IWST) dan kaedah S-Transformasi akhir, ConDAS mampu menentukan vektor anjakan yang diukur adalah ketara secara statistiknya. Stesen objek yang tidak stabil dikenal pasti dan vektor anjakannya dapat dikira. Perubahan vektor anjakan dapat digambarkan pada skrin komputer bersama dengan hasil yang bersiri masa. Hasil yang didapati daripada analisis deformasi pada ISKANDARnet menunjukkan tiada anjakan ketara dikesan dan semua stesen adalah stabil dalam ambangan pada dua tahun ini sejak 2010. Melalui kajian ini, suatu prosedur dan sistem perisian pemantauan deformasi tegap telah dicapai yang menyumbang kepada kajian deformasi serantau semasa di Malaysia.

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LIST OF ABBREVIATIONS

1-D	-	One-dimensional
2-D	-	Two-dimensional
3-D	-	Three-dimensional
BPE	-	Bernese Processing Engine
CCGE	-	Canadian Centre for Geodetic Engineering
CDDIS	-	Crustal Dynamics Data Information System
CODE	-	Centre of Orbit Determination
ConDAS	-	Continuous Deformation Analysis Software
CORS	-	Continuous Operating Reference System
DDS	-	Deformation Detection System
DGPS	-	Differential GPS
DIMONS	-	Displacement Monitoring System
FEM	-	Finite Element Model
F-Test	-	Fisher Test
FTP	-	File Transfer Protocol
GEONET	-	GPS Earth Observation Network
GLONASS	-	Globalnaya Navigatsionnaya Sputnikovaya Sistema or Global Navigation Satellite System
GNSS	-	Global Navigation Satellite System
GOCA	-	GNSS/Local Positioning Sensors/ Local
Sensors		
		based online Control and Alarm System
GPS	-	Global Positioning System
GUI	-	Graphic User Interface
IGS	-	International GNSS Service
IPGSN	-	Indonesian Permanent GPS Station Network
ISK1	-	ISKANDARnet1

ISK2	-	ISKANDARnet2
ISK3	-	ISKANDARnet3
ISKANDARnet	-	Iskandar Malaysia CORS Network
IWST	-	Iteratively Weighted Similarity Transformation
JKR	-	Public Works Department
KKPG	-	Kolej Komuniti Pasir Gudang
LAS	-	Least Absolute Sum
LPS	-	Local Positioning Sensors
LS	-	Local Sensors
LSE	-	Least Square Estimation
MATLAB	-	Matrix Laboratory
MCR	-	Matlab Compiler Run-Time
MMD	-	Malaysian Meteorological Department
MyRTKnet	-	Malaysia Real Time Kinematic GNSS Network
NEQ	-	Normal Equation
PANDA	-	Program for the Adjustment of Geodetic Networks and Deformation Analysis
PTP	-	Port of Tanjung Pelepas
QIF	-	Quasi Ionosphere Free
RINEX	-	Receiver Independent Exchange Format
RTS	-	Robotic Total Station
SAPOS	-	Germany Satellite Positioning Network
SatRef	-	Hong Kong Satellite Positioning Reference Station Network
SCIGN	-	Southern California Integrated GPS network
SiReNT	-	Singapore Satellite Positioning Reference Network
SNAP	-	Satellite Navigation and Positioning Laboratory
SPRGN	-	South Pacific Regional GPS Network
S-transformation	-	Similarity Transformation
TEQC	-	Translation, Editing, and Quality Check
TIM	-	Trimble Integrity Monitoring
T-Test	-	Tau Test
UNIBE	-	University of Bern

UTM	-	Universiti Teknologi Malaysia
VRS-RTK	-	Virtual Reference Station Real Time Kinematic
WCDA	-	Western Canadian Deformation Array

LIST OF SYMBOLS

A	-	Configuration matrix
dn	-	Difference in North component
de	-	Difference in East component
du	-	Difference in Up component
e, n, u	-	Coordinate of local topocentric system
F	-	Fisher distribution
G	-	Inner constraints matrix
I	-	Identity matrix
l	-	Vectors of observation
n	-	Number of observation
N	-	Matrix of normal equations
Q	-	Cofactor matrix
r	-	Degree of freedom
s	-	Scale
S	-	Similarity transformation
u	-	Number of parameter
v	-	Vector of residuals
W	-	Weight matrix
x	-	Matrix of parameters
x, y, z	-	Geocentric Cartesian coordinate system
z	-	Number of station within monitoring network
α	-	Significance level
α	-	Orientation of error ellipse
φ	-	Latitude of local system
λ	-	Longitude of local system
D^T	-	datum equations matrix

x^2	-	Chi-square distribution
$Q_{\tilde{d}i}$	-	Covariance matrix of d in datum *i*
u_d	-	Dimension of confidence region
d_i	-	Displacement in i^{th} iteration
$Q_{\tilde{d}i}$	-	Covariance matrix of d in datum *i*
Q_{x_i}	-	Covariance matrix of x in datum *i*
Q_{x_k}	-	Covariance matrix of x in datum *k*
σ_{EN}	-	Cofactor of easting and northing
df_p	-	Pooled degree of freedom
r_x	-	Rotation in X-direction
r_y	-	Rotation in Y-direction
r_z	-	Rotation in Z-direction
t_x	-	Translation in X-direction
t_y	-	Translation in Y-direction
t_z	-	Translation in Z-direction
u_i	-	Standard residual
v_i	-	Adjusted residual
X_a	-	Adjusted coordinate
X_i	-	Parameter in datum *i*
X_i, Y_i	-	Provisional coordinates for point i
X_k	-	Parameters in datum *k*
X_o	-	Provisional coordinate
σ_{vi}	-	The related value is taken from the cofactor matrix of the residual Q_{vi}
σ_o^2	-	A priori variance factor
$\hat{\sigma}_o^2$	-	A posteriori variance factor
$\sum X_z$	-	Summation of coordinate X for all the station within monitoring network
$\sum Y_z$	-	Summation of coordinate Y for all the station within monitoring network
$\hat{\sigma}_o^2$	-	pooled variance
σ_E^2	-	Variance factor of easting

σ_N^2	-	Variance factor of northing
$\hat{\sigma}_{oj}^2$	-	Variance factor for epoch *j*
$\hat{\sigma}_{oi}^2$	-	Variance factor for epoch *i*

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Theoretically, deformation happened due to natural phenomena such as earthquakes and subsidence as well as implication on the extraction of natural resources. Hu *et al.* (2005) have demonstrated that natural disasters are one of a problem of global concern and may cause significant impact on human, economic, social and environment and sometimes, threaten the geopolitical stability of a nation. Thus, deformation needs to be addressed carefully and justify the necessity of deformation monitoring.

As indicated by Cankut and Muhammed (2000), instead of static deformation monitoring approaches, continuous dynamic deformation monitoring methods have been increasingly used for better understanding of natural events such as earthquakes and landslides, and to monitor the stability of manmade structures such as buildings, bridges, tunnel, dams, and so on. By incorporating deformation measurements with geodetic methods, Global Positioning System (GPS) technology is the most compatible technique to assist continuous deformation monitoring, where timely detection of any deformation displacement is critical. The deformation parameters are computed and analysed in order to examine the failure of structures.

Typically, geodetic networks for the deformation monitoring purposes can be classified into two types that are absolute and relative networks. According to Denli and Deniz (2003), absolute network contains some datum points located outside of the deformable body to determine the absolute displacements of the reference points, and of object points. However, relative network has implied that all the surveyed stations and observed points are located on or within the deformable object without a set of datum constraints, and only the relative movements of the body can be detected.

Confirmation of the stability of the network points is one of the main problems in deformation analysis (Chen, 1983). The difficulty of deformation analysis in an absolute network is the identification of unstable reference points. Once the stable reference points have been identified, the only thing left is to compute the true displacement field of the object points. Alternatively, the analysis of relative networks is more complex, since if one of the point moves then all the points in the network undergo relative movements. As stated by Chen (1983), the critical issue in this case is the determination of deformation pattern in space and in time domains.

This research is inspired to establish a deformation monitoring procedure and software system for ISKANDARnet. Since the GPS continuous operating reference station (CORS) networks have increased in number and application over the last decade (Roberts *et al.*, 2002), a new GPS CORS network called Iskandar Malaysia CORS network (ISKANDARnet) as illustrated by Shariff *et al.* (2009) was utilised to perform the deformation monitoring application. Near real-time GPS data streaming and data acquisition are receivable from ISKANDARnet control centre. The required inputs for deformation analysis can only be obtained after the GPS raw data undergo all the critical processing steps using Bernese scientific processing software (Bernese, 2010).

Appropriate strategies for deformation analysis was investigated and applied to estimate the trend of movement for the monitoring network by using the developed software. Subsequently, the fluctuation of deformation displacement was visualised on screen proportional to the associated time series results. The assessment was examined in term of the feasibility of deformation monitoring procedure and software system by using existing deformation cases. As an overall, the devised deformation monitoring procedure and software system might significantly contribute to the current studies of regional land deformation in Malaysia.

1.2 Statement of Problem

Lack of deformation analytics or analyzer in Malaysia is a preclinical problem and it has been revealed that the nation is not ready to confront the natural disaster such as earthquake and landslide. Currently, the relevant landslide information was only released in the webpage of Public Works Department (JKR). Meanwhile, the earthquake information was proclaimed by Malaysian Meteorological Department (MMD). Table 1.1 illustrates the list of recent earthquakes nearby Malaysia region (MMD, 2012).

Table 1.1: List of recent earthquake nearby Malaysia region (MMD, 2012)

Date	Time (Local Time)	Location	Magnitude	Category**	Distance
07/06/2012	3.55pm	Kalimantan	3.3	Weak	127km Southwest of Tawau, Sabah.
06/06/2012	9.08am	Taiwan Region	5.8	Moderate	135km Southeast Kaohsiung, Taiwan. 1799km Northeast Kudat, Sabah.
06/06/2012	3.31am	East Coast Honshu, Japan	6.1	Strong	135km Southeast Ichihara, Japan. 4024km Northeast Pitas, Sabah.
05/06/2012	7.01pm	Northern Sumatra, Indonesia	5.6	Moderate	77km West of Bandar Aceh, Indonesia. 593km Southwest of Langkawi, Kedah.
04/06/2012	7.18pm	South Java, Indonesia	5.9	Moderate	160km Southwest Sukabumi, Indonesia. 1098km Southeast JB, Johor.

****Earthquake Magnitude Classes**

Class	**Great**	**Major**	**Strong**	**Moderate**	**Light**	**Minor**
Magnitude	**8 or more**	**7-7.9**	**6-6.9**	**5-5.9**	**4-4.9**	**3-3.9**

Table 1.1 is not the explication and promulgates only the relevant news such as date, time, location, magnitude and distance. People will not be able to estimate the impact of deformation event to the surrounded man-made structure. In addition, no comprehensive deformation analysis conducted to man-made structures. Public might concerns about the healthiness of man-made structures after an earthquake or landslide event happened.

In fact, periodically monitoring of suspicious deformable area has dramatically increased due to the growing concerns to the disasters such as landslides and man-made structural failure. Therefore, deformation analysis is increasingly noticeable due to it is concerned with determining of a measured displacement is statistically significant. The analysis can be done visually (through the use of time line, scatter, vector and other plots) and numerically. The deformation analysis is essential for providing useful information to assess seismic hazards and risks.

Thus, this research is aimed to provide the daily stability information by implementing Iteratively Weighted Similarity Transformation (IWST) and final Similarity Transformation (S-transformation) technique with the assist of Bernese GPS processing software. Meanwhile, this research was devoted to develop a deformation monitoring procedure and software system that is ease for periodic deformation monitoring, where post process the data to analyse and visualise the results.

A deformation monitoring procedure and software system can potentially add valuable information and prepare a comprehensive explication when encounter the stresses and strains due to the effects of local crustal movements. Therefore, this research is committed in establishing a deformation monitoring procedure and software system that able to ultimately observe the deformable area periodically.

1.3 Objectives of Research

This research aims to establish a deformation monitoring procedure and software system.

The objectives are specified as follows:

a) **Design and develop the deformation monitoring procedure and software system.**
Deformation analysis was conducted using in-house deformation analysis software which is developed via MATLAB language. A robust method called Iteratively Weighted Similarity Transformation (IWST) and S-transformation was implemented to locate the unstable stations within monitoring network. It also computes the vector of displacement and error ellipse in order to display the stability of each station as well as the movement trend of network. The deformation movement of horizontal and vertical component are negligible if the displacements are not exceeding the predefined threshold. The current status of network stations was recognised by looking at the fluctuation of deformation displacement on screen.

b) **Testing and analysis of the deformation monitoring procedure and software system.**
Deformation monitoring is a kind of study that requires high precision processing strategies and analysis technique. Therefore, an assessment was conducted in order to check the precision of the detected displacement vector in order to accomplish the functionality of devised procedure and software system.

1.4 Scope of Research

The scopes of this research are described as follow:

1. Research area was located within ISKANDAR Malaysia using Iskandar Malaysia CORS Network (ISKANDARnet). Three CORS; ISKANDARnet 1 (ISK1) at Universiti Teknologi Malaysia (UTM), ISKANDARnet 2 (ISK2) at Port of Tanjung Pelepas (PTP) and ISKANDARnet 3 (ISK3) at Kolej Komuniti of Pasir Gudang (KKPG), along with four IGS stations were utilised to observe GPS data and form a monitoring network. The GPS monitoring network is shown in Figure 1.1.

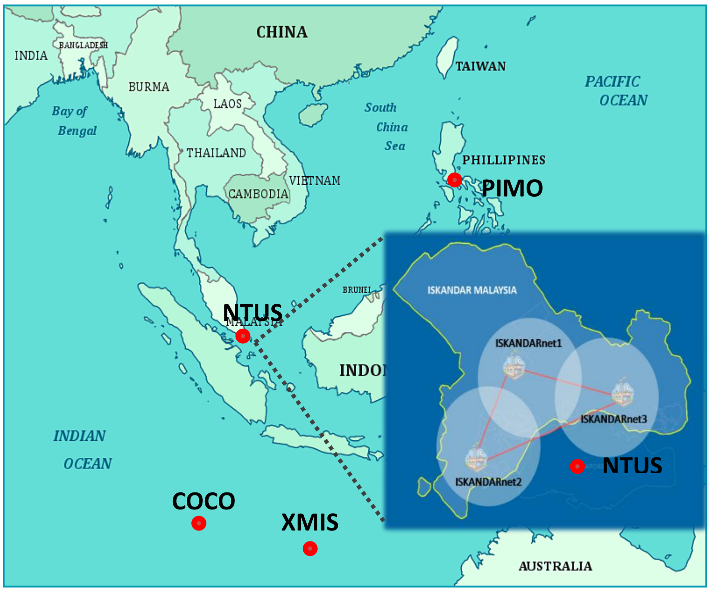

Figure 1.1: Research area for deformation studies

2. CORS coordinate monitoring or periodical deformation monitoring is the only main concern in designing this deformation monitoring procedure and software system. Thus, post-processed and analyse the GPS data was the technique employed to this study.

3. The well-established robust method known as Iterative Weighted Similarity Transformation (IWST) was applied for estimating the trend of movements

in two-epoch analysis. IWST analyse and indicates the status of stability for each network stations and S-transformation compute the displacement vectors. A rigorous statistical testing named Single Point Test was utilised to locate unstable stations. The deformation is significant if the computed displacements exceed the predefined threshold.

4. In spite of the fore mentioned issues, the technical requirements, procedures of data processing and deformation analysis are usually not similar for different cases or types of deformation. However, stability analysis of reference stations within the GPS monitoring network is only thing considered for designing this deformation monitoring procedure and software system.

1.5 Significance of the Research

This study is essential for several purposes:

1. **Deformation monitoring procedure and software system delivers positive effects to users particularly for implementing deformation monitoring applications.**
   a. The software system is able to fulfil user demand for deformation monitoring solution.
   b. The devised procedure and methodology might give some indicator to the current deformation monitoring field.

2. **Developing a new research medium of deformation monitoring in Malaysia.**
   a. Through this research, the development of a deformation monitoring software system can be experienced.
   b. The software system able to handle periodical deformation monitoring cases.

3. **The designs of deformation monitoring procedure and software system may become one of the grand contributors to the existing deformation monitoring system in Malaysia.**
   a. An optimal design of a deformation monitoring network can be established within Peninsular Malaysia.
   b. Coordinate monitoring of Local CORS network in this study can benefit the ISKANDARnet users for conducting the survey job.

1.6 Research Methodology

Initially, addressing the important of adopting appropriate research plan was essential in order to mitigate the impending challenges that occur while the research under way. Typically, this study had been conducted as illustrated in Figure 1.2. The methodology of this study consists of five stages: stage one includes review the current status of deformation monitoring procedure and software; stage two focus on the Bernese software study and data preparation for deformation detection module; stage three covers on the formation of deformation detection module via Matlab language; stage four take into account the visualisation of deformation movement on-screen and final stage was on assessment and analysis of the devised procedure and software system then draw out the conclusion. As an overall, the research methodology had been condensed into three objectives that were stated in Section 1.3. Figure 1.2 illustrates the flow chart of deformation monitoring procedure and software system that included of the 5 stages.

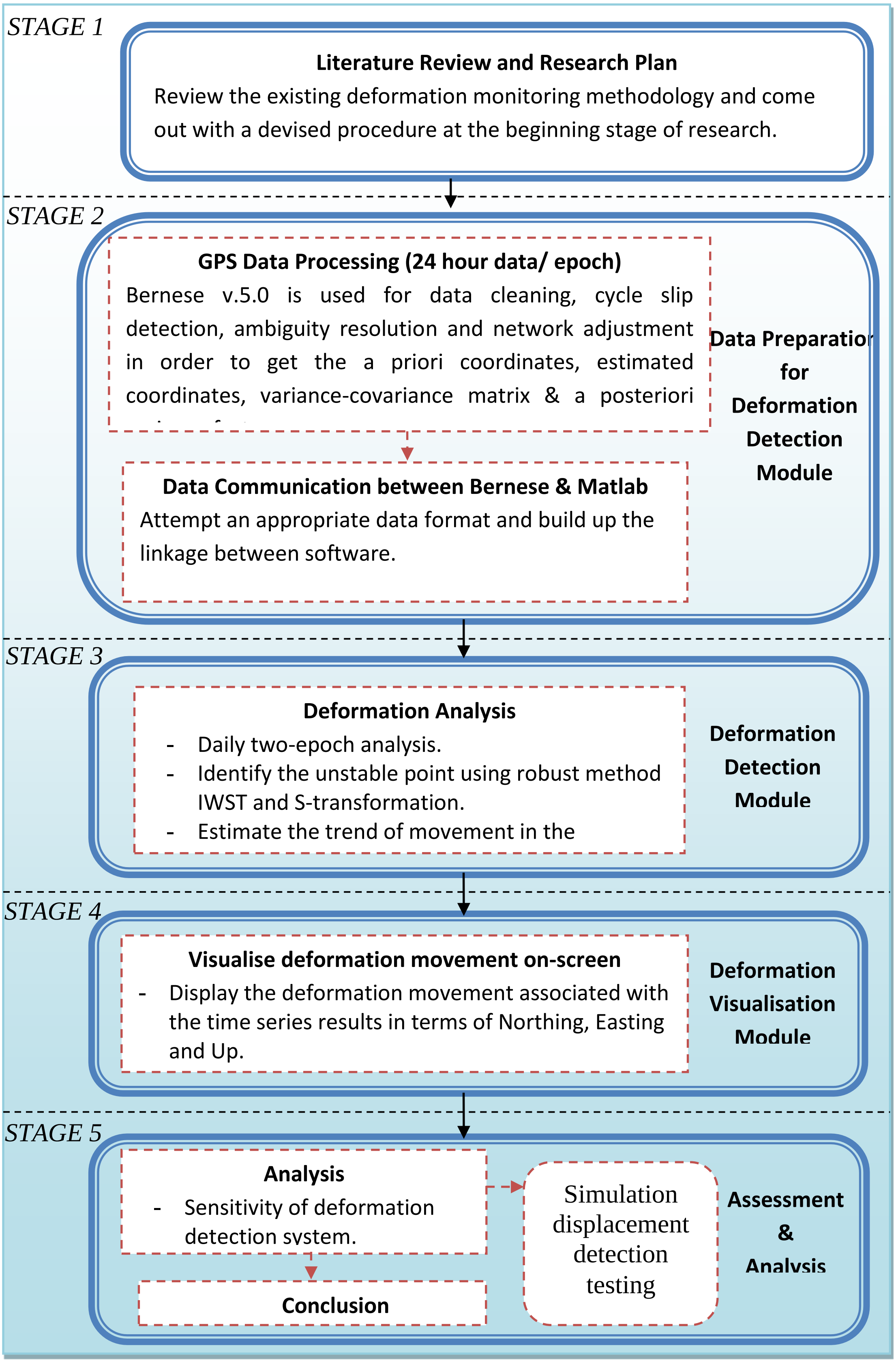

Figure 1.2: The flow chart of research methodology

1.7 Chapter Content

The development of deformation monitoring procedure and software system has been described in this thesis. The thesis contains seven chapters. First chapter include the research introduction and research plan. The second chapter discuss the current trend of deformation monitoring procedure and software. The third chapter concern the general Bernese GPS processing strategies. The fourth chapter focus on the design of deformation analysis software via robust method. The fifth chapter discuss the development of deformation monitoring procedure and software system. The sixth chapter consist of results and analysis of deformation detection in varies cases. The seventh chapter is the conclusion inclusive of the recommendation for the improvement of this research in the future. Relevant information that has not been included in the chapters was appended at the end of the thesis.

REFERENCE

Abidin, H.Z., Subarya, C., Muslim, B., Adiyanto, F.H., Meilano, I., Andreas, H. and Gumilar, I. (2010). The Applications of GPS CORS in Indonesia: Status, Prospect and Limitation. *FIG Congress*. 11-16 April. Sydney, Australia.

Acar, M., Özlüdemir, M.T., Akyilmaz, O., Celik, R.N. and Ayan, T. (2006). Deformation Analysis with Total Least Squares. *Natural Hazards and Earth System Sciences* 6(4), 663-669.

Aguilera, D.G., Lahoz, J.G. and Serrano, J.A.S. (2007). First Experiences with The Deformation Analysis of A Large Dam Combining Laser Scanning and High-accuracy Surveying. *XXI International CIPA Symposium*. 01-06 October. Athens, Greece.

Aringer, K. (2009). High Accuracy GNSS Positioning Service in Bavaria. *Croatian Positioning System (CROPOS) conference*. Ohrid, Macedonia.

Baarda, W. (1967). Statistical Concepts in Geodesy. Nethelands Geodetic Commission, *Publications on Geodesy* 8, Vol. 2(4), 74pp.

Baarda, W. (1968). *A Testing Procedure for Use in Geodetic Networks*. Nethelands Geodetic Commission. *Publications on Geodesy* 9, Vol. 2(5), 97pp.

Baarda, W. (1973). S-Transformations and Criterion Matrices. Nethelands Geodetic Commission. *Publications on Geodesy* 18, Vol. 5(1), 168pp.

Bernese (2010). Bernese GPS Data Processing Software Package, Version 5.0. http://www.bernese.unibe.ch/index.html. Accessed on: 21st March 2010

Bertacchini, E., Capitani, A., Capra, A., Castagnetti, C., Corsini, A., Dubbini, M. and Ronchetti, F. (2009). Integrated Surveying System for Landslide Monitoring, Valoria Landslide (Appennines of Modena, Italy). *FIG Working Week*. May 3-8. Eilat, Israel.

Borre, K. (1999). Index of /~borre/easy. kom.aau.dk/~borre/easy/. Accessed on: 27th September 2010.

Cankut, D. I. and Muhammed, S. (2000). Real-Time Deformation Monitoring with GPS and Kalman Filter. *Earth Planets Space*. Vol. 52(No. 10), pp. 837-840.

Caspary, W.F. (1988). *Concept of Network and Deformation Analysis*. Monograph 11, School of Surveying, University of New South Wales, Kensington, 183pp.

Chen, Y. Q., Chrzanowski, A. and Secord, J. M. (1990). A Strategy for the Analysis of the Stability of Reference Points in Deformation Surveys. *CISM Journal ACSGC*, 44(2): 141-149.

Chen, Y.Q. (1983). *Analysis of Deformation Surveys – A Generalized Method*. Technical Report No. 94, Department of Surveying Engineering, University of New Brunswich, Fredericton, N.B.

Choudhury, M.M., Rizos, C. and Harvey, B. (2009). *A Survey of Techniques and Algorithms in Deformation Monitoring Applications and the use of the Locata Technology for Such Applications*. Satellite Navigation and Positioning (SNAP), University of New South Wales, Australia.

Chrzanowski, A. and Szostak-Chrzanowski, A. (1993). Enhancement of Deformation Modelling in Engineering and Geosciences by Combining Deterministic and Generalized Geometrical Analysis. *Annual Conference of Canadian Society for Civil Engineering (CSCE)*. June 8-11. Fredericton, New Brunswick.

Chrzanowski, A. and Wilkins, R. (2006). Accuracy Evaluation of Geodetic Monitoring of Deformation in Large Open Pit Mines. *3rd International*

Association of Geodesy (IAG) / 12th International Federation of Surveyors (FIG) Symposium. May 22-24. Baden.

Chrzanowski, A., Caissy, M., Grodecki, J. and Secord, J. (1994). *Software Development and Training for Geometrical Deformation Analysis.* UNB Final Report. Contract No. 23244-2-4333/01-SQ.

Crespi, M. and Riguzzi, F. (1998). Software Package Available for Analyzing GPS Deformation, American Geophysical Union, 2000 Florida Avenue N.W. Washington, DC 20009-1277, USA. http://www.agu.org/eos_elec/98059e.html. Accessed on: 8 Dec 2009.

Dach, R., Hugentobler, U., Fridez, P. and Meindl, M. (2007). *Bernese GPS Software Version 5.0*. Astronomical Institue, University of Bern (AIUB).

Danisch, L., Chrzanowski, A., Bond, J. and Bazanowski, M. (2008). Fusion of Geodetic and MEMS Sensors for Integrated Monitoring and Analysis of Deformation. *Proceedings of 13th International (FIG) Symposium on Deformation Measurement and Analysis*. May 12-15. Lisbon.

Denli, H. H. and Deniz, R. (2003). Global Congruency Test Methods for GPS Networks. *Journal of Surveying Engineering*. Volume 129, Issue 3, pp. 95-98.

Dudewicz, E. and Mishra, S.N. (1988). *Modern Mathematical Statistics*. Wiley, New York, 838pp.

Eichhorn, A. (2007). Tasks and Newest Trends in Geodetic Deformation Analysis: A Tutorial. *15th European Signal Processing Conference (EUSIPCO)*. September 3-7. Poznan, Poland.

Erol, S., Erol, B. and Ayan, T. (2004). A General Review of the Deformation Monitoring Techniques and A Case Study: Analyzing Deformations using GPS/Leveling. *XXth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress*. July 12-23. Istanbul, Turkey.

Ghilani, C. D. and Wolf, P. R. (2006). *Adjustment Computations – Spatial Data Analysis*. (4th ed.). United States of America: John Wiley & Sons, Inc., Hoboken, New Jersey.

Geoscience Australia (2005). Continuous GPS Station Network: South Pacific Sea Level Climate Monitoring Program (SPSLCMP). http://www.ga.gov.au/geodesy/slm/spslcmp/network.jsp. Accessed on: 05th December 2009.

Haasdyk, J., Roberts, C. and Janssen, V. (2010). Automated Monitoring of CORSnet-NSW using the Bernese Software. *FIG Congress 2010*, Sydney, Australia, April 11-16.

Hamdy, A.M. and Jo, B.G. (2003), Advantage of using free network adjustment technique in the crustal movement monitoring geodetic networks. *Journal of Korean Geophysical Society*, 6, 1–11.

Harvey B. R. (1991). *Practical least squares and statistics for surveyors*. (1st ed.) Kensington, N.S.W.: The School of Surveying, University of New South Wales.

Hu, Y.J., Zhang, K.F. and Liu, G.J. (2005). Deformation Monitoring and Analysis using Regional GPS Permanent Tracking Station Networks. *FIG Working Week*. Cairo, Egypt, April 16-21.

Hudnut, K. W., Bock, Y., Galetzka, J. E., Webb, F. H. and Young, W. H. (2001). The Southern California Integrated GPS Network (SCIGN). *10th FIG International Symposium on Crustal Deformation Measurements*, pp. 129-148, March 19-22. Orange, California, USA.

International GNSS Service (2010). IGS Stations. Retrieved May 16, 2010, from http://igscb.jpl.nasa.gov/network/list.html.

Iskandarnet, (2010). *Iskandarnet status*. Retrieved May 26, 2010, from http://www.fksg.utm.my/ISKANDARnet/status.html

Jäger, R., Kalber, S. and Oswald, M. (2006). GNSS/GPS/LPS based Online Control and Alarm System (GOCA) - Mathematical Models and Technical Realisation of a System for Natural and Geotechnical Deformation Monitoring and Analysis. *Proceedings of Global Equity Organization's 7th Annual Conference.* April 26-28. Hilton New York, US.

Janssen, V. (2002). GPS Volcano Deformation Monitoring. *GPS Solutions*. 6: 128-130, DOI 10.1007/s 10291-002-0020-8.

Jia, M.B. (2005). Crustal Deformation from the Sumatra-Andaman Earthquake. AUSGEO news, issue 80.

JKR (2010). e-Bencana Alam Jabatan Kerja Raya Malaysia. bencanaalam.jkr.gov.my. Accessed on: 06th May 2010.

Kavouras, M. (1982). *On The Detection of Outliers and the Determination of Reliability in Geodetic Networks*. Technical report No. 87, Department of surveying Engineering, University of New Brunswick, Fredericton, Canada.

Khoo, H.S., Tor, Y.K. and Ong, G. (2010). Monitoring of High Rise Building using Real-Time Differential GPS. *FIG Congress 2010.* 11-16 April. Sydney, Australia.

Koch, K.R. (1987). Parameter Estimation and Hypothesis Testing in Linear Models. *Springer*, Berlin, 378pp.

Kuang, S. L. (1996). *Geodetic Network Analysis and Optimal Design: Concepts and Applications*. Chelsea, Michigan: Ann Arbor Press, Inc.

Lim, M.C., Halim Setan and Rusli Othman, (2010a). GPS Deformation Monitoring and Analysis for Local CORS Network: ISKANDARnet. *Geoinformation Scienc Journal (GSJ)*, Vol.10, No.2, pp: 1-14.ISSN 1511-9491© 2009 FKSG.

Lim, M.C., Halim Setan and Rusli Othman (2010b). Deformation Monitoring and Analysis using GPS Permanent Tracking Station in Iskandar Malaysia. *Map Asia 2010 & ISG 2010*. 26-28 July. Kuala Lumpur, Malaysia.

Lim, M.C., Halim Setan and Rusli Othman (2010c). A Strategy for Continuous Deformation Analysis using IWST and S-Transformation. *World Engineering Congress (WEC)*. 2-5 August. Kuching, Sarawak, Malaysia.

Lim, M.C., Halim Setan and Rusli Othman (2010d). Continuous Deformation Detection and Visualisation of ISKANDARnet. *International Symposium on GPS/GNSS*. 26-28 October. Taipei, Taiwan.

Lim, M.C., Halim Setan and Rusli Othman (2011a). Application of Continuous Two-Epoch Analysis to GPS Deformation Monitoring in Iskandar Malaysia. *11th South East Asia Survey Congress (SEASC) & 13th International Surveyors' Congress (ISC)*. 22-24 June. Kuala Lumpur, Malaysia.

Lim, M.C., Halim Setan and Rusli Othman (2011b). Deformation Spatial Trend Analysis for Local CORS Network: ISKANDARnet. *Map Malaysia*. 5-6 April. Kota Kinabalu, Sabah**.**

Lim, M.C., Halim Setan and Rusli Othman (2011c). Continuous Deformation Monitoring using GPS and Robust Method: ISKANDARnet. *Joint International Symposium on Deformation Monitoring (JISDM)*. 2-4 November, Hongkong, China.

Lim, M.C., Halim Setan and Rusli Othman (2011d). Present-Day Displacement and Deformation Analysis of ISKANDARnet. *10th International Symposium & Exhibition on Geoinformation (ISG 2011) & ISPRS commission II/5 & II/7 Conference*. 27-29 September. Selangor, Malaysia.

Lim, M.C., Halim Setan, Rusli Othman and A.K. Chong (2012). Deformation Detection for ISKANDARnet. (Accepted and to be published in Survey Review Journal).

Lutes, J., Chrzanowski, A., Bastin, G. and Whitaker, C. (2001). DIMONS Software for Automatic Data Collection and Automatic Deformation Analysis. *Proceedings of 10th International (FIG) Symposium on Deformation Measurements*. March 19-22. Orange, CA.

MATLAB R2010a (2010). MATLAB version 7.10.0.499 (R2010a). The MathWorks, Inc. United States of America.

MMD (2010).Malaysian Meteorological Department-Earthquake & Tsunami. www.met.gov.my/index.php?option=com_content&task=view&id=746&Itemid=954. Accessed on: 06th April 2010.

Niemeier, W., Helten, S. and Wilson, D. (2011). Coordinates for the ITER Project. *Joint International Symposium of Deformation Monitoring (JISDM)*. 2-4 November. Hong Kong, China.

NRCan (2007). Western Canada Deformation Array. Natural Resources Canada. http://gsc.nrcan.gc.ca/geodyn/wcda/index_e.php. Accessed on: 08th December 2009.

OGP (2011). Coordinate Conversions and Transforamtions including Formulas. International Association of Oil & Gas Producers (OGP) Publication 373-7-2-Geomatics Guidance Note numer 7, part 2.

Pelzer, H. (1986). Application of Kalman-and Wiener-filtering on the Determination of Vertical Movements. *Symposium on Height Determination and Recent Vertical Crustal Movements in Western Europe*. Hannover, Germany.

Rizos, C. (1999). Principles and Practice of GPS Surveying. www.gmat.unsw.edu.au/snap/gps/gps_survey/principles_gps.htm. Accessed on: 05th April 2010.

Rizos, C., Cranenbroeck, J.V. and Lui, V. (2010). Advances in GNSS-RTK for Structural Deformation Monitoring in Regions of High Ionospheric Activity. *FIG Congress*. 11-16 April. Sydney, Australia.

Rizos, C., Kinlyside, D.A., Yan, T.S., Omar, S. and Musa, T.A. (2003). *Implementing network RTK: The SydNET CORS infrastructure. 6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services*, Melbourne, Australia, 22-25 July.

Roberts, C., Morgan, P. and Rizos, C. (2002). Allan Variance Applied to Time Series Baseline Results for GPS-Based Deformation Monitoring Applications. Satellite Navigation and Positioning (SNAP), University of New South Wales, Australia.

Sagiya, T., Miyazaki, S. and Tada, T. (2000). Continuous GPS Array and Present-day Crustal Deformation of Japan. *Pure and Applied Geophysics*, 157(2000): 2303-2322.

Sedlak, V and Jecny, M. (2004). Deformation Measurements on Bulk Dam of Waterwork in East Slovakia. *GeoScience Engineering*. L(2), pp. 1-10, ISSN 0474-8476.

Setan, H. (1995). Design and Implementation of Computer Programs for Analysis and Detection of Spatial Deformation. Bulletin of Surveying, vol. 6, No. 2, pp 84-98, September 1995.

Setan, H. and Othman, R. (2006). Monitoring of Offshore Platform Subsidence using Permanent GPS Stations. *Journal of Global Positioning Systems*. Vol. 5, No. 1-2:17-21. ISSN 1446-3156.

Setan, H. and R. Singh. (2001a). Deformation Analysis of a Geodetic Monitoring Network. *Geomatica*. 55(3), 333-346.

Setan, H. and R. Singh. (2001b). *Deformation Surveying I.* Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia, Monograph I, Skudai, Johor.

Shariff, N.S.M., Musa, T.A., Ses, S., Omar, K., Rizos, C. and Lim, S. (2009). *ISKANDARnet:* A Network-Based Real-Time Kinematic Positioning System in ISKANDAR Malaysia for Research Platform. *10th South East Asian Survey Congress (SEASC)*, Bali, Indonesia, August 4-7.

Singh, R. (1999). *Pelarasan dan analisis Jaringan Pengawasan untuk Pengesanan Deformasi secara Geometri.* M.Sc. Thesis. Universiti Teknologi Malaysia, Johor Bahru.

SOLE (2008). Dynamic Earth Geology – Measuring Plate Movements. Science On the Leading Edge. http://oceanlink.island.net/SOLE/tectonics/WCDA.html. Accessed on: 18th Jan 2010.

Szostak-Chrzanowski, A. and Chrzanowski, A. (2008). Interdisciplinary Approach to Monitoring, Analysis, and Modeling of Deformations. EJPAU 11(2), #29. Available On: http://www.ejpau.media.pl/volume11/issue2/art-29.html. Accessed on : 18th Jan 2010.

Takasu, T. and Kasai, S. (2005). Development and Evaluation of GPS Satellite Orbit and Clock Near Real-Time Estimation Algorithm. *Japan Geoscience Union Meeting*. 25-27 October. Makuhari Messe, Japan.

Uotila, U.A. (1974). Statistical Tests as Guidelines in Analyses of Adjustment of Control Nets. *XIV Congress of International Federation of Surveyors (FIG), Commission 5, Survey Instruments and Methods.* September 6-16. Washington.

USACE (2002a). Preanalysis and Network Adjustment (EM 1110-2-1009). US Army Corps of Engineers, Washington, DC.

USACE (2002b). Structural Deformation Surveying (EM 1110-2-1009). US Army Corps of Engineers, Washington, DC.

USACE (2003). GPS Reference Systems (EM 1110-1-1003). US Army corps of Engineers, Washington, DC.

Vanicek, P. and Krakiwsky. E.J. (1986). *Geodesy: The Concepts*. 2nd rev. edition, North-Holland P.C., Elsevier Science Publishers, Amsterdam.

Vermeer, M. (2002). *Review of The GPS Deformation Monitoring Studies Commissioned by Posiva Oy on the Olkiluoto, Kivetty and Romuvaara sites, 1994-2000.* STUK-YTO-TR 186. Helsinki.

Vigny, C., Simons, W. J. F., Abu, S., Bamphenyu, R., Satirapod, C., Choosakul, N., Subarya, C., Socquet, A., Omar, K., Abidin, H. Z. and Ambrosius, B. A. C. (2005). Insight into the 2004 Sumatra-Andaman Earthquake from GPS Measurements in Southeast Asia. *Nature*. Vol 436, doi:10.1038.

Welsh, W. and Heunecke, O. (2001). Models and Terminology for The Analysis of Geodetic Monitoring Observations. *International Federation of Surveyor. Publication* No. 25.

Wilkins, R., Chrzanowski, A. and Bastin, G. (2003). ALERT – A Fully Automated Real Time Monitoring System. *Proceedings of 11th International (FIG) Symposium on Deformation Measurements*. May 25-28. Santorini, Greece.

Zhang, K., Hu, Y., Liu, G., Wu., F. and Deakin, R. (2005). Deformation Monitoring and Analysis using Victorian Regional CORS Data. *Journal of Global Positioning Systems*. Vol. 4, No. 1-2:129-138.